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INTRODUCTION

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THE STUDY

OF

NATURAL PHILOSOPHY,

FOR

THE USE OF BEGINNERS.

BY

CHARLES TOMLINSON.

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PREFACE.

The Readers for whom popular books on Science are obviously intended, are those who have not had the advantage of a mathematical education, nor the privilege of attending courses of lectures on experimental science. Hence it is a common practice to address the popular mind in such a manner as if it were incapable of appreciating more than the details or the curiosities of science, passing by, or making subordinate, those grand principles of nature which ought to be the object of all scientific teaching. But, since every one feels an interest in understanding something of the laws which govern the physical world, it becomes the duty of the teacher to see that his pupils (as all his readers must be considered) are impressed with clear ideas of the subject under review, so that they may not only understand that which is professed to be taught, but rise up from the perusal of the work with a desire to know more. This ought to be the effect of every well-written popular treatise. Such a treatise ought to bear the same relation to larger and more difficult works that a small boat bears to a large ship; the boat enables us to get on board the ship, and the popular treatise ought to conduct the student to higher works on the same subject.

But if scientific men are disposed to prepare popular treatises with this view, and intelligent Publishers to issue them at a price sufficient to bring them within the reach of every one, it is not too much to expect the

co-operation of the Reader in carrying out so praiseworthy an object. The Reader must be prepared to bestow a higher effort of mind in the perusal of the work than is required for the appreciation of a romance, or even of a treatise on *popular science*, as this term is often understood. He must be prepared to *study* the work, and not merely to glance over its pages. If he find it difficult on a first perusal, let him give it a second, or a third, and we may venture to assure him that his labour will not be misapplied.

In the following treatise the writer has attempted to excite an interest in the study of principles, by making facts and details subordinate to this higher aim. He might have been more successful if more space could have been allowed; but this would have defeated one of the principal objects which the Publisher had in view in proposing this series, namely, great cheapness. It has therefore been necessary to refer certain subjects to subsequent numbers, in order to deal, at greater length, with other subjects, which will not be treated of separately.

The writer has to acknowledge his obligations to his friend, Mr. E. L. Garbett, for his assistance in filling up the details and preparing the figures for this work, as well as the accompanying Treatise on Pneumatics.

C. T.

CAMDEN TOWN,
September, 1848.

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INTRODUCTION

TO THE STUDY OF

NATURAL PHILOSOPHY.

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1. When a person is released for a few weeks in autumn from the cares of business, and determines to visit some foreign country, which the facilities of modern travel may have made easily accessible, he is generally prompted to his determination by higher motives than change of scene, fresh air, and healthful exercise; or, rather, he combines these objects with the more important motive of adding to his stores of knowledge, of laying up a fund of information which will afterwards supply him with agreeable and useful topics of thought and conversation, and assist his comprehension of various books that he may desire to read. The time at his disposal being limited, he cannot do more than glance at the general features of the country he proposes to visit; but he manages to select several of the most striking objects for which the country is remarkable, and, by concentrating his attention on these, he gains clear and distinct ideas of particular facts, while, by passing rapidly over the former, he acquires a general impression of the whole.

But if our traveller should be so fortunate as to fall in with a companion on the road, who is intimately

acquainted with the country as well as with the language and the manners and customs of its people, how greatly is the pleasure and profit of the journey increased! He does not waste his time and means in the pursuit of worthless objects, but is led at once to the very things which he ought to see, is placed in the best positions for seeing them, and is told exactly what he ought to know respecting them. No wonder that our traveller is delighted with his journey. On his return home he looks out for the best books on the country he has visited, and reads them with far more interest than he would have done if he had not visited the country, or had not fallen in with an intelligent guide.

That which the guide is to the traveller, the author of this little book hopes, in some degree, to be to the reader who wishes to travel rapidly over the rich and broad domain of Natural Philosophy. Within the brief limits of this small volume we cannot do more than give a general view of the country we propose to visit, and, in order to do even this, we must travel by an express train, and acquire knowledge as we move rapidly along. At the stations a few opportunities may occur of examining some remarkable objects more in detail, and these will be not so much with a view to illustrate the nature of the country as to show the best methods of exploring it.

2. Before visiting a foreign country our first concern is as to its language. Shall we understand the language of the natives, or will they understand ours? In our capacity as guide through the regions of natural philosophy we shall chiefly use the common vernacular language. There is, however, a language used by the privileged classes, called *Mathematics*, which it is of great importance to know, since the

best letters of introduction will not admit a visitor into good society unless he is acquainted with at least the rudiments of this language: far less can he hope without it to understand the state secrets which, unknown to the crowd, nevertheless extend their influence over the whole of society. Nevertheless, as we may travel through a country and obtain a general idea of its features and natural productions, its laws and institutions, its manners and customs, without mingling with the court or the nobility, so, in natural philosophy, a knowledge of common language may enable us to take a general survey of the land and get a good deal of useful and important information.

3. Natural science, in its widest and most general sense, embraces the study of that collection of created beings and objects and of those laws by which they are governed, all of which are concisely expressed in the term *nature.* The vast accumulation of knowledge, and its unequal progress, led to a necessity, long since, of dividing the study of nature into several distinct sciences. In the first place, natural objects were separated into two grand classes, the ORGANIC and the INORGANIC; the former being eminently distinguished from the latter by the exhibition of *vital power* or *life.* Organic bodies were also found to admit of a marked distinction into *animals* and *plants;* the science of *Zoology* describing and classifying the one, and that of *Botany* the other. These sciences, which admit of many subdivisions, form, collectively with *Mineralogy*, that department of knowledge called *Natural History.*

In the second place, it was found desirable to erect into a distinct science the study of celestial phenomena which are comprised in *Astronomy.* That which remained included the study of inorganic and terres-

trial phenomena, forming 1, *Geology*, which has for its object the observation and description of the structure of the external crust of the globe; *Mineralogy*, taking account only of the separate items of which the earth's crust is composed. 2, *Chemistry*, which may be regarded as inorganic anatomy, its object being to decompose bodies, to study the properties of their elements, and the laws of combination. 3, *Physics*, or *Natural Philosophy*, properly so called, which considers the *general* properties of all bodies, and therefore, in its widest sense, includes *Chemistry* (or at least so many of its laws as are common to all substances); but the use of the term *physical* is often limited to those phenomena which do not relate to chemical composition, but appear to depend on several universal agencies, the laws and definition of which have to be sought out.

But natural philosophy, even in this restricted sense, is again subdivided into many distinct sciences. The mutual action of forces and masses of matter produces in the latter either equilibrium or motion, and hence arise those two important divisions of science called *Statics* and *Dynamics*, which are further divided into *Stereo-statics* and *Stereo-dynamics* as applied to solids; *Hydrostatics* and *Hydrodynamics* as applied to liquids; and, perhaps we may add, *Electro-statics* and *Electro-dynamics* as applied to electricity, regarded as a fluid. The application of statics and dynamics to air and other gaseous fluids is called *Pneumatics*. The application of dynamics to the arts of life has led to the composition and arrangement of the various machines for assisting the labour of man; and hence this branch of science is called *Mechanics*. The construction and performance of the various machines or engines employed to raise water, or which are driven by the

motion of that fluid, belong to hydrodynamics, (sometimes called *Hydraulics*,) while the construction of works depending on the equilibrium of liquids belongs to hydrostatics. In like manner, those machines which are driven by the wind depend on the application of pneumatics; and all the varied phenomena of the atmosphere arising from the action of heat, light, electricity, and moisture, form the science of *Meteorology*. The phenomena of *Heat* and *Electricity* also form separate sciences, the latter admitting of five divisions, namely, *Electricity*, properly so called, *Magnetism*, *Galvanism*, or *Voltaic electricity*, *Thermo-electricity*, and *Animal-electricity*. The phenomena of *Light*, although included in the general term *Optics*, are so varied as to give rise to at least *six* extensive branches of science; namely, *Perspective*, *Catoptrics*, *Dioptrics*, *Chromatics*, *Physical optics*, and *Polarization*; to which may now perhaps be added a seventh, *Actino-chemistry*.

4. It must be borne in mind that all these divisions and subdivisions of natural science are purely arbitrary, and are made for the convenience of study. They do not of course exist in nature, for the various beings and objects and phenomena of the natural world are all subject to the same general laws, and consequently are influenced by, as they are dependent on, them. It is scarcely possible to become intimately acquainted with a single phenomenon, without the assistance of several sciences. There is, however, a method of arrangement by which these sciences fall into their places in the order of their complexity; the most simple standing first, or, in other words, those groups of phenomena which depend on the most simple and general laws are taken as a basis on which to erect other groups, including the same general characters as the first group, but

having also something in addition which makes them a little more complex than the first group. In like manner a third group may be connected with the first and second, if it contains all their characters and something in addition. In this way a natural system of classification may be built up for the phenomena of inorganic matter, as it has been with such decided success in Zoology and Botany. The animals or the plants to be classified were carefully studied with a view to their real affinities, the dependence of groups upon each other being like the links of an extended chain; with this difference, that, instead of the links being all alike, the simplest is placed first: this is succeeded by one a little more complex, the third is still more complex, and so on to the end. Now, in order to get anything like a clear view of the different branches of natural philosophy, we must examine them with reference to their dependence in the order of their advancing complexity. It is evident that, as facts become multiplied, this sort of arrangement or classification is required. A number of facts are selected and arranged into a group, according to some feature peculiar to them all; and thus a sort of bundle is formed, and the common feature or governing principle forms at once a connecting tie and a label to the bundle, which is laid aside for future use. But it often happens that this connecting tie or governing principle may fail to hold together the facts thus collected. It may be no true tie; the supposed governing principle may not govern; one bundle of facts may fall to pieces as soon as we attempt to handle it: and this is a sufficient proof that some other tie must be sought. Still the very attempt to arrange facts has its use: a bad arrangement is preferable to no arrangement; for a bad arrangement may lead to a better; but no arrangement can only lead to

confusion; for, as the great regenerator of natural science has said in his own striking manner, "Truth is more easily evolved from error than from confusion."*

5. Hence the use of *hypotheses* or *theories* in science, which are often necessary to enable us not only to arrange, but also to describe, known facts. Hypotheses are sometimes as necessary as language; for without them we could neither express what is known nor even think of it intelligibly. By repeatedly exchanging one hypothesis for another the true law of nature is at length evolved; that is, those uniformities which exist among a certain set of phenomena are reduced to their simplest form of expression. A law of nature thus formed is not only remarkable for its simplicity, but for the wide range of its application; it connects into one harmonious whole numerous facts already known, and throws light upon others which had hitherto been only dimly seen. When the mind is fairly imbued with this law in all its generality, a separate effort of memory is no longer required for each fact, for the law is so comprehensive, that it not only enables the mind to retain facts, but assists it in discovering others, and in observing them in nature, under a variety of circumstances where their presence was not before suspected.

Thus an hypothesis is useful in arranging facts, and thereby assisting the memory to retain them, even though it be not a true expression of nature. It may contain a part of the truth, and gradually lead to the evolution of the real law. By observation and experiment facts are established; by arranging and rearranging facts under one or other hypothesis, a principle or law of nature is at length brought out, and this method of dealing with or generalizing facts is called

* Lord Bacon.

induction, and forms the grand instrument of investigation in physical inquiries.

6. Hence arises one of the most important points of distinction between *physical* and *abstract* (or mathematical) science. The latter proceeds chiefly by *deduction*, or descent from generals to particulars, starting from the fundamental ideas of space and number, and following them into more and more intricate combinations and ramifications; while natural science, on the contrary, is *inductive*, its constant object being to generalize or collect many particular facts into one general expression or law, and many such laws again into one still more general principle; thus, not only extending our knowledge, but condensing it into smaller and smaller compass. Indeed, although the number of known *facts* is continually increasing, the number of acknowledged *principles* is being constantly reduced; and the former object is to be considered as merely secondary and subservient to the latter, which is the true aim of physical science. Hence, however paradoxical it may appear, it is, nevertheless, true, that in proportion as natural science is advanced, and the laws of nature become fairly established, the less we have to remember.

7. The objects of all natural science may therefore be regarded as threefold. *First*, the *discovery of laws*, or the generalization of the facts or phenomena of nature, and their reduction to the smallest possible number of principles. This object is the only one of the three which admits of being attained completely. In two of the above-named branches of science, (dynamics and astronomy,) it has actually been so attained; and they are thus removed from among the inductive and placed among the deductive sciences, their induction being already completed.

Secondly, the *determination of data*, as they are called, that is to say, of certain quantities which must be known (or their ratios to each other known) before the laws can be applied deductively to predict any fact or phenomenon. The most perfect knowledge of the laws of planetary motion, together with perfect mathematics to apply them, would not enable the astronomer to predict the place of a planet at a given instant of time, unless he knew its place at some other given instant *, together with certain particular dimensions †, which fix the form, size, and position of its orbit. So, with all other natural laws, they are too general to admit of particular application, unless we have particular *data*, which must be determined either by direct measurement, or by mathematical reasoning, or calculation founded on such measurement; and as these measurements can never be perfect, nor even so accurate as to render greater accuracy useless, it is evident that this object, the determination of data, must be regarded as one which we are constantly approaching without ever completely attaining, although the progress of science furnishes the means of attaining greater accuracy.

Thirdly. The ultimate object for which the two former objects are pursued, is the *deduction* from these laws and data of the facts or phenomena that may arise from new combinations of circumstances, or the determination of the mode in which we must combine circumstances so as to produce a given result. It is here that the truth of the famous aphorism "knowledge is power" becomes realized. But it is here also that we perceive most clearly the inefficiency of human knowledge; for if the first of the objects above proposed be completely attainable, while the second can only be at-

* Technically, the *epoch*. † Technically, the *elements* of its orbit.

tained by approximation, this last, on the contrary, can be approached only in the way that a balloon may be said to approach the stars. To say that our deductions from a law, when it is once established, are limited only by the extent of our mathematics, is to pronounce them limited indeed; for it is in mathematical, far more obviously than in physical, science, that we find ourselves, in the words of our great countryman, "picking up a few pebbles on the sea-shore," while the great, the infinite ocean of truth lies all undiscovered before us.

8. We may cite as an illustration of these views the law of gravitation, which regulates the celestial motions. It is the simplest that could be imagined, namely, that bodies attract each other directly as the mass, and inversely as the square of the distance*. Now it is the object of physical astronomy to deduce from this one simple law all the motions of the bodies (about thirty in number) which constitute the planetary system to which we belong. This has been done so far as to leave no reasonable doubt that it might be done completely, if the problem were within the reach of mathematical science. But this science, or our application of it, has a limit. The motions of *two* bodies gravitating towards each other may be deduced without much difficulty; but let a *third* body be introduced, and let the three all mutually attract each other, and the problem becomes the most difficult that our mathematics has yet solved. There is no hope at present that the motions of *four* bodies mutually acted on by this simple law could be deduced; and it is only on account of the immense disproportion between the masses of the sun and of the largest planets, and between these and the

* It has been proved that a force varying inversely as the *simple distance* instead of its *square*, although enounced in simpler terms, would, nevertheless, lead to more complex results.

smaller ones, that astronomical events can be predicted so accurately. This fortunate disproportion renders a sufficient degree of accuracy attainable without considering the action of more than three bodies *at once*.

This will give some idea of the feebleness of deductive science, and its utter incompetency to deduce from the simple laws of dynamics and gravitation any of the great mass of every-day terrestrial motions. If the "problem of *three* bodies" be the highest that has ever been solved deductively, what shall we say to the problem of *innumerable* bodies which is presented to us in every terrestrial phenomenon?

9. The first problem of physical science then is,—given the *phenomena* to find their *law*. The second is,—given the *law*, and some of the *phenomena*, to find those quantities which are to serve as *data* for the prediction of other phenomena. The third problem is an inversion of this:—given the *law*, and these *data*, to foretel the *phenomena*. Now, though the first of these problems is, as we have seen, the only one that can be completely solved, yet it is the only one which *cannot* be reduced to a logical form; it is the only one which cannot be solved by rule. It is plainly, from its enunciation, what mathematicians call an *indeterminate* problem; that is, the premises are insufficient to determine or fix the conclusion; whereas, in both the other cases, they are sufficient; for we have *two* things given to find *one*. While these, therefore, come under the rules of strict reasoning, the first problem can only be solved as it were by hypothesis, by successive *guesses* and *trials;* for the truth of a law arrived at by induction cannot be known, except by reversing the process and deducing the phenomena from the law. No general rules, then, can be given for induction, or

the discovery of a law from a set of phenomena, any more than the chemist can give rules for analyzing substances that contain unknown ingredients; for such rules for induction (could they be given) would, as Sir John Herschel remarks, include the whole of inductive science. Induction would no longer be required, its object being attained and its problem solved at once in all its generality, so as to render all further solutions of particular cases unnecessary.

But although this great and primary object of natural science cannot be reduced to rules, yet many philosophers have done great service by collecting, arranging, describing, and reasoning upon the various methods that have most frequently led to its attainment. The first of these was Lord Bacon, who, without being a discoverer of physical truth, became, nevertheless, the founder of natural philosophy, by first pointing out this its true object, and suggesting the modes by which it might be expected to be attained. The carrying out of his suggestions has led to all the valuable discoveries of the last two centuries; and it may be doubted whether this great *mental* discovery did not display a vaster effort of mind (as it has certainly a wider generality of application) than any of the physical discoveries that have arisen from it.

To enumerate the principles applicable to inductive reasoning would be out of place in this little book. The reader who wishes to see them brought together, classified, and explained, is referred to the valuable works mentioned below*; but there is one of these

* *Discourse on the Study of Natural Philosophy*, in the Cabinet Cyclopædia, by Sir John F. W. Herschel.

The History and the Philosophy of the Inductive Sciences, by the Rev. Dr. Whewell. In five large volumes.

A System of Logic, by John Stuart Mill, forming a connected view of

principles which, from its beauty and its direct bearing on natural theology, must not be passed over.

10. In all his inquiries the natural philosopher is greatly assisted by *analogy.* In the broad truths or laws of nature which have been once established there is so much simplicity, such manifest design, that the same Almighty hand is everywhere discernible. Nature is made to work by the simplest means; the design is uniform in that which we understand, and we look for simplicity and uniformity of design in that which we are endeavouring to make clear.

Many of the most successful hypotheses, or *guesses* at natural laws, have been originally suggested by this principle of analogy. We must be careful, however, not to rely too implicitly on such suggestions; because infinite *variety* is no less a principle of nature than perfect *unity;* and in placing too much dependence on the latter we may forget the former. A remarkable instance of this occurs in the history of the science of light. It was by analogy, derived from the case of sound, that Huyghens was led to found his beautiful theory of light, on the supposition that it consisted in a vibratory motion transmitted through a supposed universal fluid in the same way that vibrations are transmitted through air. But although the reality of the undulatory theory of light has been rendered more and more probable by the remarkable and unexpected agreement of this theory with every subsequent discovery, yet it has been shown that the analogy which led to this happy idea was unfounded, the waves or vibrations of light being communicated in a totally different mode from those of sound, namely sidewise, instead of directly forward; for while sound is propagated by each particle

the principles of evidence and the methods of scientific investigation. In two large volumes.

of fluid pulling or pushing its neighbour as it were backwards and forwards, in light each particle urges the next one laterally, namely to the right or to the left.

11. We have spoken of the value of hypotheses in connecting facts until science is ready for their more complete generalization into a law of nature. The history of science furnishes many instructive instances of the mode in which an hypothesis is superseded by a law. For example, it was an hypothesis with the ancient philosophers that "nature abhors a vacuum," and they were naturally led to it by observing that not only did no vacuum or empty space exist in the world, but that all attempts to form one were defeated by the unexpected entrance of some kind of matter in obedience to no known natural law except that implied in the above assertion. Thus, if one end of a tube be immersed in water, and the other end be placed in the mouth, on sucking out the air the water will rise in the tube. The same thing happens in a pump: one end of the barrel dips into the well, and by working the piston contained in the barrel the air is extracted and the water rises. These and numerous other facts, hypothetically connected by the term *suction*, were referred to nature's antipathy to a vacuum; but it so happened, that on the erection of a pump at Florence, it was found impossible to raise the water to the surface. This excited great astonishment; and, upon inquiring into the circumstances, it appeared that the distance from the piston of the pump to the surface of the water in the well exceeded thirty-four feet; and this appeared to be the source of failure.

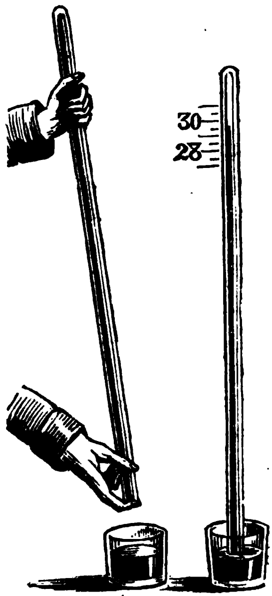
Galileo was consulted, and it is now a matter of doubt whether his solution of the difficulty was given satirically or seriously. His reply was, "that nature's abhorrence

of a vacuum extended only to the height of thirty-three feet." This peculiar predilection of nature for a certain number of feet was, indeed, the only way of reconciling the old hypothesis with the new facts; but it placed this hypothesis in a ridiculous light, and did not remove the difficulty in the case of the Florentine pump.

The great question to be solved was, "Why does water rise in a pump?" Torricelli, an illustrious disciple of Galileo, brought together all the known facts of the case, with the addition, however, of one new feature, which had hitherto been omitted in the inquiry. Up to this time air had been supposed to possess no weight, because a bladder full of air was found to weigh no more than when empty. It was forgotten that a bladder filled with water, or even quicksilver, and immersed in the same fluid, would give just the same result, and would seem to weigh no more than when empty. This shows how cautious we should be to avoid the danger of a *false* induction, which often, as in this case, lurks under an outward appearance of the strictest logic. Perceiving the unsoundness of this inference, then, Torricelli supposed that the air might have some weight; and thus a new and most important condition was added to the facts of the case. Discarding the old hypothesis, we may suppose him to reason thus:—If the weight of the atmosphere is capable of supporting a column of water thirty-three feet high, it will support a higher column of a fluid lighter than water, and a shorter column of a fluid heavier than water. Now, as mercury is nearly fourteen times heavier than its own bulk of water, the same force which supports a column of water thirty-three feet high can only support a column of mercury about two and a half feet high. In order to test this new hypothesis,

Torricelli took a glass tube about three feet long, shut at one end; and, having filled it quite full of mercury, he closed its mouth with his finger, and, then inverting the tube, placed its open end in a basin of mercury. (Fig. 1.) The finger was then withdrawn, and the mercury in the tube fell a few inches, but remained stationary at a height of about thirty inches above the level of the mercury in the basin, leaving the upper six inches of the tube a *vacuum*, which, in honour of the inventor of this experiment, has been named the *Torricellian vacuum.* Now the cause of the suspension of this mercury was rendered evident by carrying the whole apparatus up a lofty tower or a mountain; for it was found that the higher we ascend (that is to say, the *less air* we have above us) the *less* height of mercury is supported in the tube.

Fig. 1.



By this capital experiment, then, the old hypothesis of nature's abhorrence of a vacuum was at once and for ever set aside, and all the phenomena of suction were brought under the beautiful and comprehensive law of atmospheric pressure, depending on the weight of the atmosphere. It was found that a column of water of any thickness, and thirty-three feet high, was of the same weight as a column of mercury of the same shape and thickness, and thirty inches high. Supposing these columns to

be an inch square, they will each weigh between fourteen and fifteen pounds, which is therefore the weight of a column of atmospheric air an inch square, extending from the level of the sea to the top of the atmosphere.

As a natural consequence of this truth, it was found that whenever (from any cause) the density of the air varied, a corresponding change took place in the height of the column of water, mercury, or other fluid, in the exhausted tube. Pascal established the truth of this conclusion so thoroughly, as to propose this tube of mercury as a means of estimating the heights of mountains more easily than by direct measurement; and this method of *levelling* has now been brought to such perfection, that heights calculated in this way are found to differ by not more than one per cent. from the measured height. It was also found, on watching the column of mercury from day to day at the same spot, that its height was subject to considerable variations, thus indicating corresponding variations in the atmospheric column. By measuring these changes by a fixed scale, the *barometer* rose into existence; and, in almost the very same form in which it was bequeathed by Torricelli, it now constitutes one of the most important of our meteorological instruments.

12. Should the young student in science be disposed to undervalue this great discovery on account of its apparent simplicity, we must remind him that this constitutes one of its chief merits. The laws of nature, when freed from hypotheses, are just as remarkable for their beautiful simplicity as the false hypotheses have been for their unwieldy complexity. The most striking instance of this is seen in the planetary system. How different was the cumbrous machinery of hollow "crystalline spheres," or the "cycles and epicycles scribbled

o'er," from the simple plan that now amuses children; but it is not more difficult to liberate the beautiful statue which by a poetical fancy may be supposed to lie concealed in the rough block of marble, than to extricate one of nature's laws from the mass of crude hypothesis which surrounds it; because all this hypothesis becoming mixed up with our real knowledge, and forming part of our education, belongs to our habits of thought, and becomes engrafted as it were into our mental constitution, so that we cannot think of certain phenomena except by the hypothesis which binds them together. What idea have we, for example, of the immense assemblage of wonderful and beautiful facts which constitute electrical science, unless we are allowed to use the hypothetical term *electric fluid*, and to suppose that this fluid moves in what is called an *electric current?* Let any one try to think of electricity without the use of this hypothesis, and he will feel how difficult, how impossible, is the effort. In the same way, if our education in natural philosophy had engrafted upon our minds, as an important truth, the dogma that nature abhors a vacuum, we should regard almost as impious the attempt to produce a vacuum; we should feel that we were acting in opposition to natural laws. But such men as Torricelli, who are among the lights of the age in which they live, do succeed in overcoming the strong prejudices of their education: they strike out new trains of thought for themselves, and bring new territories under the dominion of man. And in such men there is always something to admire in addition to their scientific discoveries. Do we not feel that our love of nature receives additional encouragement and sanction when we know that our own Newton was good as a Christian as he was great as a philosopher; and is not our

admiration of Torricelli exalted when we find him lamenting that his discoveries had not fallen to the lot of his master, Galileo?

13. Before the reader proceeds to the study of natural philosophy, he ought to form a clear idea of what science is actually capable of teaching, and what is the limit of her pretensions. Now science regards all phenomena as subjected to invariable natural laws, the precise discovery of which, and their reduction to the least possible number, are the objects of inquiry. Science does not deal with the generating causes of phenomena; she only analyzes with accuracy the circumstances of their production, and connects them by relations of succession and similitude. There can be but one cause for the varied phenomena of nature, and that is nature's God. "The Lord hath made the earth by his power, he hath established the earth by his wisdom, and hath stretched out the heavens by his discretion." * Consequently, in the operations of nature, *design*, not *necessity*, is manifest. And here we see another important difference between mathematical and physical science. The former confines itself to those truths which are true of *necessity*, or which we cannot conceive to be otherwise. Thus we cannot conceive that twice three can be seven, and if we take any more complex mathematical truth, (for instance, that the surface of a globe is four times the area of a circle of the same diameter,) though this may not be obvious, yet, by a long chain of deductive reasoning, we can prove it to be as *necessary* a truth as that twice three are six. But physical facts are true only by *design;* we could conceive them to be different. We endeavour to understand the design of a physical law, and, when understood, we could fancy a different design leading to

* Jeremiah, x. 10.

different results; hence, a physical law is not a necessity arising from the nature of things, but dependent on the will of God, for God could easily have given them a different nature; but, in doing so, He would have had a different design. Science, then, no longer busies herself, as formerly, about *causes* either efficient or final, since all we can or need know on this head is, that the final cause of all phenomena is the design of God, and the efficient cause His will. When any phenomena therefore are said to be explained or accounted for, all that is meant by this is, that they are generalized, or included in a general *law*—not that their *causes* are better understood than before. The object of induction is not to account for facts, but to generalize them; not to discover their *causes*, but their *laws*. For example, we say that the chief phenomena of the universe are explained, i.e. *generalized* (but not *accounted for*), by the Newtonian law of gravitation; because, on the one hand, this splendid theory exhibits to us all the immense variety of astronomical facts as only one and the same fact seen in different points of view—the constant tendency of all the particles of matter towards one another in the direct ratio of their masses and the inverse ratio of the squares of their distances; while, on the other hand, this general fact is presented to us as the simple extension of a phenomenon which is perfectly familiar to us, and by it alone we consider as perfectly explained the gravity of bodies at the surface of the earth. But while it explains (i.e. *generalizes*) these phenomena, it can in no way be said to *account for* them, or to answer the simple question which is said to have led to this grand discovery—namely, why does an apple fall? Nor should we understand the cause of this the more, were gravitation itself explained, that is, removed from the rank of primary

into that of secondary principles, by a further step in generalization showing it to be only a particular consequence of a still more general law.

This important distinction between the useless and now abandoned pursuit of *causes* and the useful pursuit of *principles*, may be further shown by another example:—It is a common property of matter to expand by heat and contract by cold; a solid, a liquid, or an air, occupies more space at a higher than at a lower temperature, and this is so generally true as to become a law of nature. To this law, however, there are a few apparent exceptions, which are as much, or even more remarkable proofs of design than the law which they appear to disturb. For instance, the proposition that water expands by heat and contracts by cold is only true within certain limits. Above the temperature of 39½° it obeys the general law; at 212° it becomes steam, and the steam also obeys the general law; but below 39½° the law is no longer obeyed; it appears to be actually reversed; for then water expands by cooling and continues to do so until it reaches 32° or the *freezing point*, when it undergoes a further and sudden expansion in becoming solid ice. Then the general law comes again into operation, for the ice contracts by cold and expands by heat as other solids do.

This exception to the general law of expansion appears to operate in the following manner. As bodies contract by cold, they occupy less space and become specifically heavier; that is, denser. Now, in the process of freezing, the water at the surface being first cooled, becomes heavier and sinks; a fresh portion of water is thus brought to the surface, becomes cooled in its turn and sinks; the process thus goes on until the surface water reaches the temperature of about 39½°, when, instead of contracting and becoming hea-

vier by cold, it begins to expand and becomes lighter than the water beneath, so that it remains surface water and forms a crust of ice, which protects the water beneath from the freezing influence of the air; for it is another beautiful provision that ice and water are very bad conductors of heat. Were it not for this very beautiful exception to the general law, every layer of water, in cooling, would sink until the whole mass of water was brought to the freezing point, when it would become solid from the bottom upwards; its inhabitants would be destroyed; the heat of summer would be insufficient to melt it; the earth would be covered with glaciers, and the cheerful temperate climates would become even more desolate than the present condition of the frozen regions of the pole.

14. Now it is evident in this case that we can refer the cause to a design of God for the good of his creatures in this planet. Thus the fact is sufficiently *accounted for*, but not *generalized*. It remains (with a few others*) an apparently outstanding exception to an otherwise universal law; just as before the time of Torricelli the facts of suction stood out as exceptions to the law of gravity, of which they nevertheless are

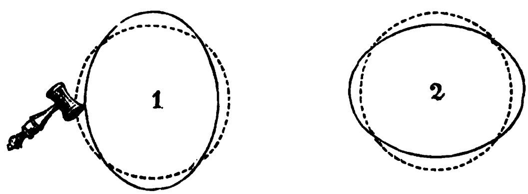
* There are one or two other such apparent exceptions which might be regarded as mere curiosities. One of them occurs in *antimony*, a metal little known out of the museum or the laboratory; and yet, but for this property of a certain rare mineral, this little work, now in the reader's hands, would probably never have reached him, nor would far more valuable works have effected one tithe of that diffusion of knowledge which we now enjoy. It is by the admixture of a small portion of antimony in the *lead* of which types are cast, that this metal is prevented from contracting (like other bodies) as it cools. Were it not for this the sharp indentations of the mould would remain unfilled, rendering it necessary that each individual type should be chased or carved separately, instead of thousands being cast in one mould. Thus the expense of printing would have been increased perhaps a hundredfold, and its benefits diminished in far greater proportion.

now seen to be mere consequences. In the same way there can be no doubt that when, by an increased insight into the molecular constitution of bodies, the present supposed law of expansion by heat shall be included in some more general law, of which it is only a consequence, these seeming exceptions to the supposed law, or *hypothesis*, will be found to be mere consequences of the true law, or *theory*. And while this will not diminish our admiration of the divine design and foresight, it will greatly enhance our admiration of the divine wisdom; which is displayed far more in thus achieving seemingly incompatible ends, by the operation of general laws, than by ordering arbitrary exceptions to them. In fact, the necessity for such exceptions in human laws is a plain proof of their imperfection, which has to be corrected by afterthoughts. To impute such defects to the laws of nature would be utterly at variance with every notion of divine perfection. These apparent exceptions to a natural law show that we have not arrived at the true law or theory, to which they will be found to be no exceptions, but mere results of its operation, guided by divine contrivance; just as the invariable length of a compensation pendulum is no exception to metallic expansion; but, on the contrary, a result elicited from it by human contrivance, which is far better displayed in the invention of such a pendulum, than in passing an act of parliament, and then correcting some blunder in it by an arbitrary exception.

15. As this is a point of some importance, it may be useful to take another illustration. When one event is always immediately followed by another, uneducated persons are usually satisfied with the explanation that the first is the *cause* of the second. Without doing more than just glance at such notions as a wet Saint

Swithin's day producing a succession of six weeks' rain; or the wars of Napoleon being a consequence of certain meteorological and astronomical appearances in the sky; let us take an example, which is at least free from the taint of superstition, such as the stroke of a bell being the cause of sound. Now the most superficial analysis of these two events will prove them to be only the first and last terms of a series of mere effects, between each term of which series we may again insert a series of intermediate effects; and this interpolation may be continued without end. The blow changes the form of the bell from a circle to an ellipse,

Fig. 2.



in which two segments are within and two other segments are without the circle formed by the rim of the bell when at rest (see Fig. 2, 1); this elliptical form being itself the complex result of the action of innumerable molecular forces, by which it has been ordained that all the particles of the solid shall act on each other. The metal, by the further action of these forces, (constituting what is called its *elasticity*,) returns to its circular form with a continually increasing velocity, which by the time it has recovered that form has given it a momentum which does not allow it to stop suddenly; the part which was driven in by the stroke, now flies out as much beyond the circle of repose as it was driven within it by the stroke, and in doing so draws-in the two other segments which before were without,

thus changing the form to another ellipse (Fig. 2, 2), whose length lies in the same direction as the breadth of the former, and which is equally the result of the combined action of all the molecular forces. It will be understood that the accompanying figures greatly exaggerate the ellipticity, which is in reality so small that the derangement of the circular shape cannot be discerned by the eye. This action, by which two ellipses alternately cross each other at right angles, is repeated several hundred times within a second of time, until the force of the stroke is expended; each vibration having been less than the preceding one, because a small portion of momentum is spent in moving the surrounding particles of air, which are resisted by, and in their turn have to move, the next particles; for all the particles of this fluid (like those of a solid) act on each other by certain molecular forces which constitute its elasticity. Hence no particle can be moved without moving all the surrounding particles, and any motion (such as that of the bell) is gradually propagated to a greater and greater distance around, and distributed through a greater and greater quantity of air, till the momentum is divided among so many particles, that the motion of each one is no longer perceptible. Thus the bell by its vibrations generates a system of *waves* in the air, commencing with those particles in contact with the bell, which in their turn propagate their motion to the air around, by moving backwards and forwards, that is *vibrating* through a small space, somewhat as the waves are propagated in a field of standing corn by the vibration of the separate ears.

Now when we are said to hear the stroke of the bell in question, we do so by a process as complicated as that which set the bell in motion, and propagated the aerial waves. Some of these waves reaching the outer

ear, and agitating the air within it, communicate an equal amount of vibration to a little membrane stretched across a cell in the head, in which are arranged a series of little bones, the first of which, called the *malleus* or *hammer*, is attached to the membrane of the tympanum or drum of the ear, as it is called, and transmits its motion to a little bone called the *incus* or anvil; the vibrations travel from this to a minute bone called the *os orbiculare* or rounded bone, the smallest in the human body, and from this to the *stapes* or stirrup, so called from its exact resemblance to a stirrup iron. The stapes is connected with a membrane, which closes three semicircular canals filled with water, and lined with an expansion of the auditory nerve, which takes up the vibrations which the mind then, and not till then, recognises as the stroke of a bell.

Now any one of this chain of events may be called the *effect* of any one that precedes it, or the *cause* of any of those that follow it; but however immediate the connection may seem between one link and the next, we can always insert, or imagine inserted, some intermediate link, which might be an effect of the first, and a cause of the second.

16. Without attaching any further importance to these illustrations and speculations than as tending to show the vagueness of the terms *cause* and *effect*, and the inutility of the search after causes instead of principles, which are the proper objects of physical inquiry, let us now proceed to notice some of the most general properties of *matter;* a term which is applied to all those substances which are appreciable by the senses, and of which the mind can conceive no two portions to occupy the same space at the same time. Hence the two necessary and essential properties of all matter are *extent* or *volume*, and *impenetrability*.

It is impossible to form any conception of matter without allowing it some extent; for the smallest conceivable speck must have length, breadth, and thickness; and must therefore occupy a space into which a second speck cannot possibly enter until the first has moved away. This is all that is meant by the *impenetrability* of matter.

17. The quantity of space which a body occupies is called its *volume* or *bulk*. The external limits of the volume of a body are one or more *surfaces; lines* or *edges* are the limits which separate the several surfaces of the same body when it has more than one. The quantity of surface is called its *area*, and the quantity of a line is called its *length*. The term *space* is sometimes applied in this latter sense to denote *length* or *distance*, sometimes to denote *area;* but in physical science it most commonly denotes *volume* or *bulk*. The properties or mutual relations of these three kinds of space, and the modes of comparing their quantities, belong to abstract science, namely, to that branch of mathematics (or the science of quantities) which is called *geometry* (or the science of space).

18. In the measurement of distances the natural philosopher avails himself of the beautiful truths which geometry has made susceptible of rigid demonstration, and the results brought out are, of course, equally true, whether applied to exceedingly small or to vast distances.

Persons are often startled at such large numbers as those which represent the distance between the sun and the earth. A very moderate acquaintance, however, with geometry, will enable any one to see the nature of the principles upon which such results are based; principles which are founded upon pure truth, and do not admit of doubt. If there is any doubt, it must be ap-

plied to the experimental observations, to the measurements of the base lines and the angles, &c.; but the apparatus employed is so delicate and exact, and astronomers have so many methods of *proving* their results, and of comparing them with results obtained by other widely different modes of observation, that it is in most cases quite as impossible to refuse assent to the great accuracy of the observations as to the perfect accuracy of the calculations founded on them. Persons who are fond of science would find their pleasure greatly increased by endeavouring to understand the principles upon which certain results are obtained. It is not always easy, or even possible, without high mathematical attainments, to follow the astronomer or the natural philosopher in all his reasonings; but it is generally possible, with a moderate knowledge of elementary mathematics, to form a tolerably clear idea of the principles applied. For these and other reasons, some of which have been already stated, the reader should always prefer those books which make facts subservient to principles, to those which deal only, or chiefly, with facts. It has been well said, that "in science facts are the soldiers, but theory (that is, true theory) is the general;" each equally helpless without the other, but combined accomplishing great things.

19. Let us first endeavour to gain an idea of the methods by which science measures exceedingly small distances, such as the thousandth or the millionth of an inch, because it is on the measurement of these minute portions of space that the accuracy of astronomical observations depends. All these observations consist in the measurement (with the greatest possible exactness) of some *angle*—the inclination of some two lines, real or imaginary. Of course this can only be effected by a graduated arc or curved scale,

which is called the *limb* of an instrument. Most complex machinery, and exquisite contrivance, are used for ensuring the equality of all the divisions engraved on this limb, and of which, in many cases, there are 100 or more in every inch, so that a microscope is required to ascertain which division is nearest the index or moveable part of the instrument. Still, however, (unless the instrument were of an unwieldy size,) this would be far from giving the degree of nicety required, even in the every-day observations of the navigator, were it not for a most valuable contrivance called the *vernier* *, which enables us to estimate spaces 10, 20, or even 60 times less than the divisions of the limb, however small they may be.

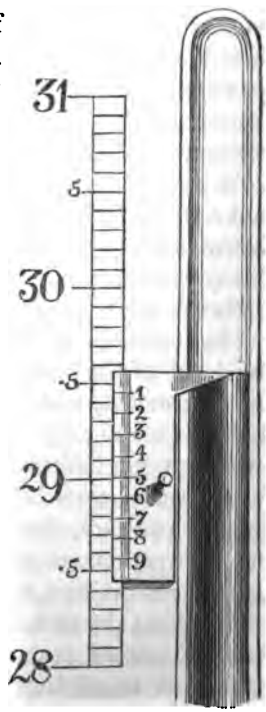
As a *vernier* is attached to every common *barometer*, (not a wheel barometer,) a reference to that household instrument will enable us to explain the principle of this contrivance.

Now it must be understood that the scale attached to the common vertical barometer actually begins at the level of the mercury in the cup at the bottom of the instrument, and is continued upwards to 31 or 32 inches. (See Fig. 1.) In the barometer constructed for carrying up in balloons, or to the summits of mountains, for measuring their heights by the diminution of atmospheric pressure, the whole of the scale is attached, but in instruments in common use the lower part of the scale is omitted, the part attached beginning somewhere about the 28th inch, as the mercury never sinks below that mark at or near the level of the sea; and as each inch is subdivided into tenths, the height of the column in inches and tenths is to be ascertained at a

* From the name of the inventor, Peter Vernier, a French gentleman, who described it in a tract printed at Brussels in 1631. It is also sometimes called a *Nonius*, from another inventor.

glance; bùt the tenths of tenths, that is, the hundredths of an inch, require for their determination a little more attention, for the engraving of nine lines between each of those usually engraved would greatly increase the expense of the instrument, by requiring a finer material for the scale, and great care to ensure the equality of so many and such small divisions. But the necessity for these is obviated by the vernier, which is a little sliding scale attached to the side of the large scale, as represented in Fig. 3. It measures exactly one inch and one-tenth in length, and is divided into ten equal parts, numbered from the top downwards, while the divisions of the inches of the scale are numbered in the figure from the bottom upwards.

Fig. 3.



Now as ten divisions on the vernier are equal to eleven on the scale, and as those ten are all equal to each other, it follows that each division of the former must be equal to $1\frac{1}{10}$th division of the latter, or to $\frac{11}{100}$ths of an inch. If, therefore, any division on the vernier coincides, or is in a line with a division on the scale, the two lines immediately above or below those which coincide will be separated by a distance exactly equal to $\frac{1}{100}$th of an inch; the pair two degrees removed from the first has a deviation of $\frac{2}{100}$ths

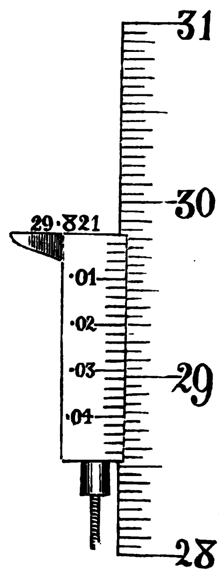
of an inch, and so on. Thus, in the engraving, the line marked 6 on the vernier coincides with the line 28·9 on the scale, but the two lines immediately above them (marked 5 and 29) do not exactly coincide; and this want of coincidence must, from the nature of the case, amount to $\frac{1}{10}$th of $\frac{1}{10}$th of an inch, or $\frac{1}{100}$th of an inch. In the next two lines, marked 4 and 29·1, it will be seen that they fail to coincide by $\frac{1}{10}$th of $\frac{2}{10}$ths of an inch, or $\frac{2}{100}$ths of an inch: in like manner, the lines marked 3 and 29·2, 2 and 29·3, 1 and 29·4, and 0 and 29·5, deviate from each other respectively by $\frac{3}{100}$ths, $\frac{4}{100}$ths, $\frac{5}{100}$ths, and $\frac{6}{100}$ths of an inch. The same reasoning will also apply to the lines situated below the coincident lines marked 6 and 28·9: thus 7 and 28·8 immediately below them fail to coincide by $\frac{1}{100}$th of an inch, and so on with respect to the others. The point which the reader has to bear constantly in mind is, that a division on the vernier is $\frac{1}{100}$th of an inch larger than a division on the scale.

In applying the vernier to measure off small fractions of an inch in the oscillations of the barometer we first notice the height of the column by the fixed scale, which in our figure indicates more than $29\frac{1}{2}$ inches, or 29·5, but less than 29·6. In order to ascertain how much of the next tenth of an inch is omitted in this statement, we place the zero, or 0, of the vernier scale exactly level with the top of the mercury; we next observe that, out of the eleven lines of the vernier, only one will coincide with a line on the scale. In our figure the line marked 6 on the vernier coincides with a line on the scale, and as from the top of the mercury to these coincident lines there are six pairs which do not coincide, and as each pair deviates by $\frac{1}{100}$th of an inch more than the pair below it, the uppermost pair must evidently differ by $\frac{6}{100}$ths of an inch. We thus

arrive at the conclusion that the height of the mercury in our figure is $29\frac{1}{2}$ inches and $\frac{6}{100}$ths of an inch, or, expressed decimally, 29·56.

In the above example we have preferred, for the sake of simplicity, to take the largest (as well as simplest) case of the application of this principle; but it is obvious that, if the fixed scale be divided into twentieths of an inch, a vernier equal in length to 11 of these divisions, and divided into 10 parts, would enable us to carry on our measurement to the 200th of an inch; but if the vernier were as long as 21 of the fixed divisions, and were divided into 20 parts, it would enable us to estimate the 20th of a 20th, or the 400th of an inch. In this case a small lens might be necessary, both for placing the zero (or 0 division) of the vernier, with sufficient exactness, level with the top of the mercury, and also for deciding which of the 20 pairs of lines came nearest to a coincidence, and if this were found impossible, on account of two adjacent pairs appearing both equally coincident, then we should be justified in "splitting the difference," thus descending in our statement to the 800th of an inch.

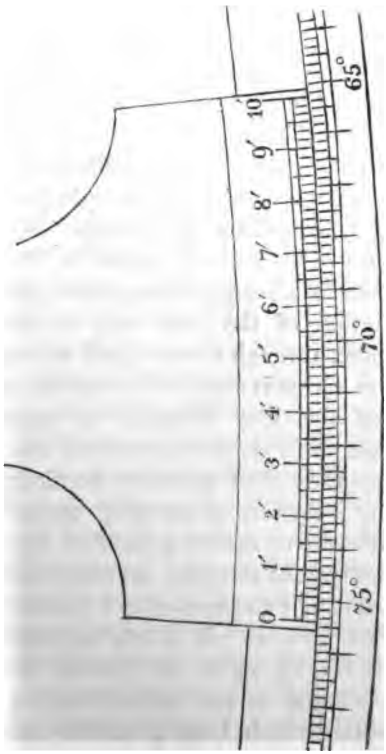
Fig. 4.



Again, if the fixed scale remain as just described, and the vernier be made as long as 26 of its divisions, and be divided into 25 parts, each of these will exceed a division of the fixed scale by a 25th of a 20th,

that is, a 500th of an inch, and as this is halved when two pairs of lines appear equally coincident, we thus see how, without the use of any divisions smaller than the 20th of an inch, the height of the mercurial column is estimated to *three* places of decimals, or to *thousandths* of an inch*, as in most meteorological registers.

Fig. 5.



20. Of course the same principle, here applied to a *straight* scale, is equally applicable to the *curved* limb of any astronomical instrument. Thus Fig. 5 represents a portion of such a limb divided into spaces of 10′, which are further subdivided by the vernier, which having 60 divisions corresponding to 61 on the limb, enables us to estimate a sixtieth of 10′, namely 10″. It is represented as indicating 75° 24′ 25″. A real instrument of this size (15 inches

* Such an arrangement was intended to be shown in Fig. 4, but the lines being coarsely engraved, four pairs appear to coincide, and the reading might be taken for 29·820, 29·822, 29·824 or 29·826.

radius) would probably measure single seconds, for, being engraved on silver or platinum, the divisions would generally be made at least three times as small as here shown. Instead of six, there might be twenty in each degree, and (each of these being 3′) a vernier with 90 divisions, corresponding to 91 on the limb, would suffice to indicate seconds. Even the common "box-sextants" used in surveying, whose limb is less than 3 inches long, and divided into 120 degrees, have these degrees halved, and the vernier having 30 divisions enables us to measure single minutes, or even half minutes, in a good instrument of its kind.

But for such measurements neither the naked eye nor the naked hand is sufficiently delicate to place the index or vernier in its right position. The eye must be assisted by a telescope or microscope, and the hand with what is called a "*slow motion*," that is, some mechanical arrangement, by which a considerable motion of the hand may be necessary to move the index through a very small space, and for this purpose the *screw* is applied in various modes. The screw itself also may be made to subserve the purposes of minute subdivision, provided the spaces between every two threads of the worm be made very regular. Thus, for every turn of the screw upon its axis, the index will advance or recede a distance equal to that between two contiguous threads; and for a half or quarter-turn, the advance or recession will be the half or the quarter of this interval. It is easy to determine these quantities, by tracing upon the border of the head of the screw (enlarged to any extent required) a division of equal parts, which bear a known relation to the principal scale; for if this gradation of the circle be into 100 equal parts, then, in turning the screw one of these parts, the motion of the index will amount to only the

$\frac{1}{100}$th part of the distance between the two contiguous threads of the screw.

It would be impossible here to enter into the modes by which this *mechanical* principle is combined with that of the vernier, and with still more exquisite *optical* contrivances, in the use of the various kinds of the micrometers by which angular measurements are "read off;" but these examples will be sufficient to show, that (with instruments constructed and fixed at the expense of nations, and with all the improvements that the accumulated experience of many lives could suggest,) we need not doubt the possibility of astronomers measuring the inclination of two given lines (real or imaginary) to within *half a second*, or half of the 60th of the 60th of a degree.

21. Let us now notice some of the methods adopted for the measurement of great distances. For this purpose we must refer the reader to one of the simplest of abstract truths, Euclid, B. VI. prop. iv. It is one of the most useful properties of triangles, that when two of these figures have their angles equal, each to each, they will be similar to each other, differing only in scale. There is scarcely an instance in science, where it is necessary to estimate the extent of magnitudes, in which the measurement is not effected by this principle. Suppose it is required to find the *exact* distance of some object A, Fig. 6, separated from us by a river or an impracticable tract of ground. Two spots, B and C, are chosen, the distance between which can be easily measured. An angular instrument being then planted at B, the telescope is pointed successively to the other station C, and to the distant object A, and the angle through which the telescope must be moved, in turning from one object to the other, is carefully measured. The instrument is then removed to C, and, by a similar

Fig. 6.

process, the apparent or angular distance between A and B, as seen from C, is measured. Now, if we draw upon paper any line such as *b c*, and from its two extremities, set off by a protractor, two other lines, making the angle at *b* equal to that which was measured at B, and the angle at *c* equal to that measured at C, the two lines thus drawn must (if continued) meet at the point *a*, and they cannot be made to cross at any point either nearer or more distant than *a;* and the little triangle *a b c* must be equiangular, or *similar*, to the great one A B C; so that, as the length of *b c* is to that of *a c*, so is the length of B C to that of A C, and, the three former lengths being measured, the last is found by the rule of three; or if the line *b c* were drawn to any scale, if, for instance, it contained as many inches as B C does chains, then we may be certain (if light travel in straight lines) that A C measures just as many chains as *a c* does inches.

But whatever may be ascertained theoretically by this method, which is called *plotting*, or *construction*, (that is, whatever *might* be so ascertained, supposing the drawing *perfect*, and the lines to have no thickness,) may also be ascertained by trigonometrical calculation; for it is the object of trigonometry to compute by numbers every thing that might be discovered by the intersection of straight lines; and it is needless to say that this numerical method is the only *practical* one, since

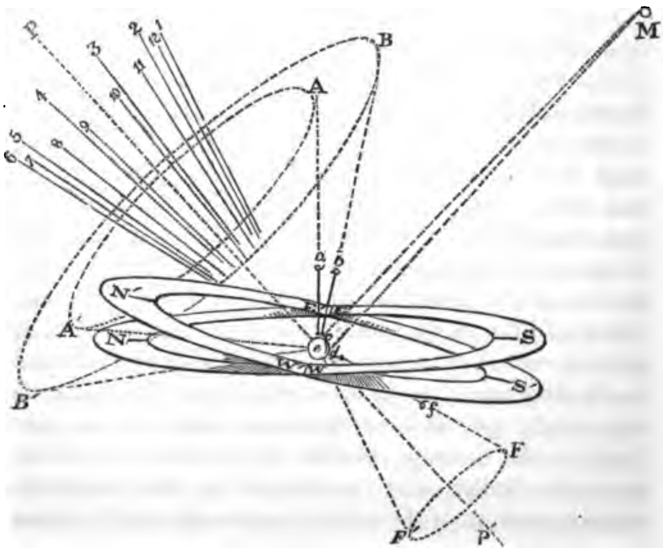
it is free from all the sources of error arising from the thickness, or want of straightness, in artificial lines. An angle can hardly be plotted on paper to the accuracy of one, or even five *minutes* of a degree, but calculation can be carried to a *second*, or to any number of decimal places.

22. By an extension of the same principle, we may ascertain the exact curvature of any part of the earth's surface in any given direction, and hence (by repeating such measurements in various parts) her exact form and size. To understand how this is done, we must first remember that a very ordinary degree of attention to the appearances presented on travelling over the land or sea is sufficient to show that (abstracting the effect of hills on the one, or waves in the other) their general convexity is very nearly equal everywhere and in all directions; or, in other words, that this planet is very nearly *spherical*—a conclusion which is strengthened by the analogy afforded by the forms of all the heavenly bodies, and confirmed by the invariably *circular* outline of the earth's shadow cast on the moon in an eclipse.

Admitting the earth's general form to be *nearly* globular, let *e*, Fig. 7, represent this *general* form; a plane touching it at any point (without reference to the *particular* form of that part of the surface) is called the *horizon* of that point, and whatever surface coincides or is parallel with this plane is called horizontal or *level* (as the surface of a calm liquid), while any line perpendicular thereto is called *vertical* (as a plumb line). Hence it is obvious that these terms have only a local meaning; that no two spots, however near, can have their horizons coincident or parallel, (as is proved by the visible want of parallelism in two parts of the same liquid surface, if its extent exceed a mile or two,) and

consequently that no two plumb lines can be perfectly parallel unless they be on opposite sides of the earth.

Fig. 7.



Now suppose we measure along the earth's surface from the point whose horizon is N E S W, or where a plumb line hangs in the direction *a e*, to the point whose horizon is N′ E′ S′ W′, or where the plumb line hangs in the direction *b e*. If we could measure the angular inclination to each other of these two horizons, or of these two plumb lines, we should plainly ascertain at once the *distance at which they would meet if continued downwards*, or, in other words, the *radius of curvature* of this part of the earth's surface. But to render this inclination (viz., the angle *a e b*) appreciable, the two plumb lines must, even at their lower ends, be many miles apart. How then is their differ-

ence of direction to be measured? Only by reference to the heavenly bodies. Now if from any part of the earth we observe another body (a star for instance) in the direction *e* 1, after two hours we shall see it in the direction *e* 2, and at intervals of two hours it will be successively seen in the directions *e* 3, *e* 4, *e* 5, *e* 6, *e* 7, *e* 8, *e* 9, *e* 10, *e* 11, *e* 12, and *e* 1, having in 24 hours appeared to describe a circle round some point in the prolongation of the line *e* P; which imaginary line, continued indefinitely both ways, forms an *axis* round which the earth must be supposed to revolve once in 24 hours. Now we must bear in mind that the distance of the stars and most other foreign bodies is so incomparably greater than any line we can measure on the earth's surface that they have no *parallax*, that is, the uniformity of their apparent hourly motion is in no way affected by being viewed from various parts of the earth, the only difference of thus viewing them being that the axis P P′ is differently inclined to the horizons of different places; more inclined, for instance, to the horizon N E S W, than to N′ E′ S′ W′. Now these inclinations may obviously be measured by simply taking the mean of the *greatest* and *least altitudes* of the star in question, as seen from each station. Thus, if from the first station we take the two altitudes, N *e* 6 and N *e* 1, their mean will be the angle N *e* P, which will be the same whatever star were observed, and is called the *latitude* of the place whose horizon is N E S W. In the same way the latitude of the other place (whose horizon is N′ E′ S′ W′) will be N′ *e* P, found by taking the mean between N′ *e* 6 and N′ *e* 1. Now suppose the two places to be on the same meridian, or north and south line, their difference of latitude thus found is plainly nothing else than the inclination of the two horizons N E S W and N′ E′ S′ W′, or the two plumb lines *a e* and

b e *. Regarding the earth then as a perfect globe, if the distance measured were 69 miles, and the difference of latitude observed were 1°, we have only to state this rule of three ;—if we must travel 69 miles to make the direction of the plumb lines vary 1°, how far must we travel to make its direction vary through 360°? The answer, of course, is 360 times 69, viz. 24840 miles = the earth's circumference. But if the earth be not perfectly globular, this will be detected by the measured length of a degree being different at different parts of her surface, or in different directions. Thus the length of a degree of latitude is found to be rather greater near the poles than elsewhere, and to diminish regularly as we approach the equator, showing the curvature (in a meridional direction) to be rather more rapid at the equator, and slower towards the poles ; so that each meridian is not circular, but rather elliptical, the shortest diameter being the earth's axis, as Newton foretold by *deduction* from his theory, long before these measurements were made accurately enough to discover it inductively. As this ellipticity or compression, however, does not exceed $\frac{1}{300}$th of the earth's diameter, its effect on the length of the degrees may in most cases be neglected †.

* This is only one out of many methods which will readily occur to the reader. Thus, suppose we observe at the first station that a certain star passes daily over our zenith ; or, in other words, that our plumb line *e a* points once every day towards a star, which star appears daily to describe the circle A A′, whose apparent or angular diameter, A *e* A′, is 84° ; the half of this, or 42°, is then the star's *polar distance* or *co-declination*, and also the place's *co-latitude*. But at the second place, the plumb line *e b* points once a day to a different star, which appears to describe the larger circle B B′, so that its polar distance P *e* B is 55°, which is also the co-latitude of this second place ; then we know that their difference of latitude is 13°.

† The measurement of degrees of the meridian, for the purpose of ascertaining the size of the earth, have been undertaken in various countries with extreme accuracy. The arc measured by the French extended from

Knowing then the dimensions of our globe, we may, from the observed positions (or latitudes and longitudes) of any two spots on its surface, calculate their *distance*, either measured over the earth's convex surface, or in a straight line through its mass. This latter distance, then, may be made the base of a triangle extending to any heavenly body visible from both places at once; for though the angles of this triangle cannot be measured directly (because the two stations are not visible from each other), yet we can at each station measure the angular distance of the heavenly body from the *earth's axis*, which we have seen to be a fixed line whose position can always be determined at any spot (indeed it has to be determined before even a *sun-dial* can be properly fixed). Thus, suppose two observers on the same meridian, but one in the northern hemisphere at *c*, where the plumb line *b e* makes an angle of 55° with the axis P P′, and the other in the southern hemisphere at *d*, his plumb line *f d* being inclined 21° to the same axis. This he knows, because a star in his zenith F appears daily to describe the circle F F′, whose diameter (*i.e.* the angle F *e* F′) is 42°. Their difference of latitude, then, or the angle between the two plumb lines *b c* and *d f*, is $180° - 55° - 21° = 104°$; so that their distance, measuring over the surface, is 104 times 69 miles (the measured length of a degree in round numbers), but their distance in a straight line through the

Dunkirk to the southernmost point of the Balearic Islands, including 12° 22′ 14″, having its centre half way between the equator and the north pole. Another survey of this kind was performed by Mason and Dixon, on a part of the shore of Pennsylvania, which happens to be so straight and level as to admit of a line of more than 100 miles being measured *directly*, without triangulation. Very long lines have also been measured (trigonometrically) by order of the English Government, both at home and in India, the mean result of which makes the earth's axis 7898 miles 5 furlongs 16 yards, and the diameter of the equator 7924 miles 7 furlongs.

earth must be found by further calculation, which will give about 6238 miles. It will be plain, also, that the inclination of this line to the earth's axis is half the difference between 55° and 21°, viz. 17°. Now suppose that, on the same day, and at the moon's culmination (which is necessarily simultaneous at both places if they are on the same meridian), they each observe her polar distance, *i.e.* the observer at *c* takes the angle P *c* M, while the observer at *d* at the same moment takes P′ *d* M. Let the former be 88° and the latter 93° 30′. The excess of their sum over 180°, viz. 1° 30′, is obviously equal to the angle *c* M *d*, one of the angles of our triangle. To find the other two at its base *c d*, we must, as this base is inclined 17° to P P′, add 17° to one of our measured angles and subtract it from the other. Having thus found all three angles, and one side *c d* = 6238 miles, we shall find the other sides *c* M and *d* M to be each about 237,000 miles, which is the mean distance in round numbers between the earth and the moon.

When the *distance* of a body is known, we can at once find its *size*, and *vice versâ*, by the simplest application of similar triangles. Thus, suppose a disc 1 foot in diameter must be removed to the distance of exactly 110 feet from the eye, in order that it may just conceal the moon and no more. It is evident that her distance at that moment must be 110 times her diameter; so that if the former has been found to be 237,000 miles, the latter is 2160 miles. We shall find, however, that her distance varies at different times from $115\frac{1}{8}$ to $103\frac{5}{8}$ times her diameter, while that of the sun varies from $109\frac{1}{3}$ to $105\frac{3}{4}$ times his diameter.

23. But the moon is the only heavenly body whose *absolute* size and distance can be found directly in this way (by what is called her *parallax*), for in our figure the moon and earth are represented rather too near, so

that the angle $c\,\text{M}\,d$ is rather too large; and when it is remembered that the sun is 400 times more distant than the moon, it will be seen that in his case this angle (or his parallax) would be too small to be measured directly. There are *mechanical* modes of finding his distance (by the theory of gravitation), but it would probably never have been found by a purely *geometrical* method (or apart from all theory), were it not for the assistance afforded by the planet *Venus*.

Fig. 8.

This planet, as is well known, can never be seen in the middle of the night, but is alternately a morning star for about 10 months, and an evening star for the same period, appearing to oscillate alternately to the right and left of the sun, never preceding or following him by a longer interval than 3 hours. Her brightness varies; and, when viewed through a telescope, this is found to arise from her undergoing all the varieties of form and size represented in Fig. 8. When first appearing as an evening star (or a little to the left of the sun, as at 1), she appears very small, but *round*, like a full moon; as she proceeds eastward (or remains vi-

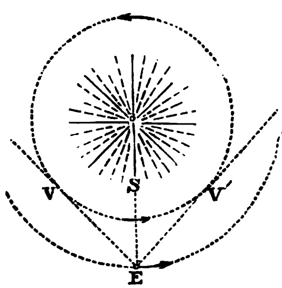
sible longer and longer after sunset, as at 2, 3, 4), her size seems to increase, but her form to *wane* or become *gibbous;* and when she has attained her greatest eastern elongation from the sun, as at 5, so as to set as late as possible, viz. about 3 hours after him, she resembles a *half-moon*, and her rapid increase in size shows that she is approaching directly towards us. She then turns sunward, very slowly at first, but with increasing rapidity, at the same time increasing in size, but diminishing in *phase*, so as to become *horned*, as at 6. Yet the former increase exceeds the latter decrease up to a certain point, as at about 7, where she attains her maximum brilliancy, as seen by the naked eye. After this, towards 8, her bright crescent, though enlarging, becomes so rapidly thinner that she appears to grow fainter and fainter, till lost in the glare of the setting sun. But a few days after this, she appears just before sunrise, having passed from the *left* to the *right* of the sun, as at 9. At first she is a thin crescent, but as she rapidly travels westward, (or rises earlier every morning,) the crescent grows thicker though smaller, till, about 10, the maximum brightness is again attained, as at 10, or 35° from the sun, after which the diminution of size more than compensates for the increase of phase. The motion becomes slower and slower, as at 11, till, at about 45° from the sun, (or when she precedes him by three hours, as at 12,) she again turns sunward, her phase being then exactly *half*, and her diminution of size very rapid, showing her to be receding directly from us. She then continues to increase in phase but diminish in size, as at 13, 14, 15, 16, and to rise later, till lost in the beams of the rising sun. Her disappearance this time, however, *behind* the sun's glare*,

* Technically her *superior conjunction.*

lasts five times as long as the previous one* when passing *before* it; and, indeed, her whole eastward passage from 12 to 5 occupies about fifteen months, while that from 5 to 12 occupies only five.

Now, if her positions at certain equal intervals (say every month) be laid down as in Fig. 8, preserving her correct apparent distances from the sun, and also her correct relative sizes and phases, it will be impossible to resist the inference that she travels in a nearly *circular* orbit round the sun, and the exact size of this orbit, compared with the sun's distance from us, will be found simply by measuring her greatest angular elongation from him to the right and left. Thus, suppose these elongations to be 45°, then draw such a diagram as Fig. 9, where E represents the earth. Let the lines E V and E V′ make angles of 45° with E S. If we draw a circle round the sun with such a radius, that it shall just touch these lines E V, E V′, without cutting them, this will plainly give the true size of Venus's orbit (supposed to be circular), compared with the distance between the sun and the earth; and it will be seen that she has *three* times farther to travel from V′, round beyond the sun to V, than from V to V′. Every other circumstance also confirms this conclusion, and exact observations show that her distance from the sun is never less than ·71837 nor more than ·72829 of the earth's *mean* distance from him. Venus's orbit is more nearly circular than

Fig. 9.



* Technically her *inferior conjunction*.

that of the earth, though this latter is less eccentric than that of any other planet.

But it is plain that the earth's motion round her orbit, in the same direction as Venus, but more slowly, must make a material difference in these appearances. If, however, we regard both orbits as circular, (which is very nearly the case,) it will be seen that the only effect will be to make Venus appear to occupy a longer time in running through these changes than she really takes to make one revolution. The true period is only 224 days, while the apparent, as we have seen, occupies about twenty months, or 584 days, viz. the time during which the two planets, after starting from a conjunction, will come to a conjunction again, (as the two hands of a clock come together after 1 hour 5 minutes and $\frac{5}{11}$,) for during 584 days the earth has made about one revolution and $\frac{8}{13}$, while Venus has made $2\frac{8}{13}$.

But when we speak of Venus as passing *before* the sun, it must be remembered that she does not generally pass exactly before his *body* but a little above or below*, in consequence of the inclination of the plane of her orbit to that of the earth. The various planets and satellites do not move in the same plane; if they did, every conjunction of three bodies would cause a *transit*, *occultation*, or *eclipse* †. But this cannot take place

* That is, to the *north* or *south* of the straight line joining the sun and earth. Though the terms *up* and *down* have no meaning in universal nature, yet they are constantly used by astronomers (as in the expressions *ascending* and *descending* node), all such expressions being understood with reference to a spectator standing on the earth's northern hemisphere. To residents in the southern hemisphere these terms must be very perplexing.

† These are only different names for the same phenomenon, which is called a *transit*, when a smaller body appears to pass before a larger which it is unable to hide; an *occultation* when the nearer body is (in appearance) larger than the other, so as to hide it completely; an *eclipse* when they are nearly equal, or whenever the *sun* is hidden from any body, by the shadow of another.

with the sun and Venus, unless she be in her conjunction and at the same time near one of her *nodes*, or points where she crosses the plane of the earth's orbit. We are opposite these points on every 6th of June and 7th of December; therefore, when Venus is in inferior conjunction on or very near one of these days, she will be seen to pass before the sun's body like a black spot. But this is so rare an event that it has only happened twice since the revival of science.

The first time this was observed was on the 4th Dec. 1639, or 24th Nov. O. S., not by an Astronomer Royal, surrounded with every means of exact observation, but by a young man of twenty, furnished with no other instrument than a piece of smoked glass. This individual, named Jeremiah Horrocks, had, by deduction from the true system of astronomy, (then hardly established,) been led to expect this effect, overlooked by Copernicus and his successors. On the day which he had calculated, he began to watch the sun from his rising till the hour of attending Divine worship, for it was Sunday, and we are told that he did not allow this duty to be interfered with by his observations. Between the morning and evening service he again watched the sun, without success. At length, towards sunset, the expected spot made its appearance, and the truth of the new theory received one more in addition to its many other confirmations.

He showed that the next transit would take place in 1761; and as this year approached, far different preparations were made from the smoked glass of Horrocks 120 years before. It was to observe this transit that Captain Cook was sent on his first voyage to Otaheite, and that other astronomers dispersed themselves over various parts of the world; for Dr. Hooke had shown the value of such an observation as the *only means* of

Fig. 10.

arriving at the absolute sizes of the orbits of Venus and the earth, and hence determining the *scale* of the solar system, till then known only as regarded its *proportions.*

To understand the principle of this measurement, we must remember that the *relative* distances of the three bodies were already known, that is, the ratio of the two distances A V and V *a* (Fig. 10) was known. Let us call this ratio (in round numbers) as 3 : 7. The transit was observed from two very distant spots on the earth, as A and B; an observer at A looking along the white line, so as to see Venus enter upon the sun's disc at *a*, and pass across it by the lower dotted line, while the observer B, looking along the dotted white line, sees her enter at *b*, and pass along the upper dotted track. Now the latitudes and longitudes of A and B being known, their direct distance through the earth is also known: let us call this 6000 miles. If *a b* were parallel with A B, it would evidently bear the same ratio to it that V *a* bears to V A*; but this

* The triangles *a* V *b* and A V B being similar, because two straight lines that cross (as A V *a* and B V *b*) make the opposite angles equal.—*Euclid* I. 15.

ratio is known, whence (calling it 3 : 7) the distance *a b* is known to be 14,000 miles; and if it be not parallel to A B, their inclination is known and allowed for. Thus much had been ascertained before the observations, the only object of which was to determine what ratio the distance *a b* bore to the whole diameter of the sun *. It was found to be (in this case) only about $\frac{1}{63}$ of his diameter, which must therefore be 63 times 14,000 or 882,000 miles; and as his distance from the earth varies, as we have seen, from 105$\frac{3}{4}$ to 109$\frac{1}{3}$ times his diameter, this distance must be from 93,272,000 to 96,432,000 miles.

Another transit of Venus took place eight years afterwards, which was observed with equal care; the next, however, will not happen till 1874, and again in 1882.

24. These observations furnished the *scale* of the solar system, for any more distant body can now be measured by its *annual* parallax, *i.e.*, by its change of place when seen from opposite sides of the earth's orbit, or at intervals of six months, after allowing for its own motion. Thus, the distance of the new planet, Neptune, is found to be about fifteen times the diameter of the earth's orbit. But this method does not succeed when applied to the bodies foreign to our system. The base

* This was found indirectly by simply observing the exact *duration* of the transit at each station, for as the dotted track *b* is longer than *a*, it is plain that the transit would last longer as seen from B than from A. The best result was obtained from the comparison of Captain Cook's observation at Otaheite with that of Planmann at Cajaneburg, in Finland. The transit lasted about six hours at each station, and fifteen minutes longer at one than at the other. The extreme beauty and exactness of this method arises from the whole being made to depend on one simple measurement, the *duration* of the transit; and from this being ascertainable with the minutest accuracy, because the moments of *internal contact*, i.e., when the outline of Venus was first or last enclosed in that of the sun, could plainly be found to a fraction of a second, or more exactly than any other astronomical event, except the similar one of the formation or rupture of the ring in an annular eclipse.

of 190,000,000 miles, furnished by the diameter of our orbit, is yet insufficient for erecting a triangle that shall reach even to the nearest *star*. The two legs of this triangle seem parallel, nor can the nicest observations yet made detect an inclination of 1″ between them, though even then they would not meet at a less distance than 216,000 times the base, or 72,000 times the whole diameter of the known solar system. Thus these bodies are proved to be *suns*, for no body smaller or less luminous than the sun could be *seen at all* at their distance.

25. The same principle (commonly called that of *similar triangles*), which is thus applied to the measurement of great distances is equally applicable to that of very small ones, too small to be measured by any arrangement of verniers or micrometers. The natural philosopher can estimate so minute a distance as the half of a millionth of an inch, which is the commencement of Newton's scale of the *colours of thin plates*, or of the degrees of thinness indicated by the appearance of certain colours, (like those seen in a soap bubble, or a film of grease floating on water, or the thin film of oxide or tarnish seen on old weather-worn glass, or on metals,) for Newton proved that the *colour* of any part of such a film depends entirely on its *thickness;* so that it may be taken as a measure thereof, when we have once ascertained the thickness necessary to produce each colour. Such measurements as these are not, of course, measured by the hand, nor appreciable by the eye, but they are based upon the unerring principles of geometry, and ascertained with precision by an extension of the reasoning powers far beyond the limits of the senses.

If we take two apparently flat pieces of plate glass, perfectly clean, and press them firmly together, a

number of beautiful colours will be seen arranged in a certain order, and forming curves more or less regular. The same colours may be seen in several minerals which crystallize in thin plates, or laminæ. The colours are produced in all these cases by a thin film of air confined between the plates. Now the question which Newton proposed to himself was to ascertain the thickness of a film of air necessary to the production of these colours. In order to render the phenomena permanent and to produce them at pleasure, this great philosopher invented the following ingenious contrivance:—He procured a plano-convex lens, the radius of whose convex surface was 28 feet; and a double convex lens with a radius of 50 feet. That is, in the first case, if we suppose a solid globe of glass 56 feet in diameter, a piece of any size, cut off from it in any way by a plane surface, would form a plano-convex lens of 28 feet radius; and, in the second case, the globe being 100 feet in diameter, two such pieces cut off it, and placed with their flat sides together, would form a double convex lens of 50 feet radius, the convexity of which would, therefore, scarcely be perceptible if the lens was small.

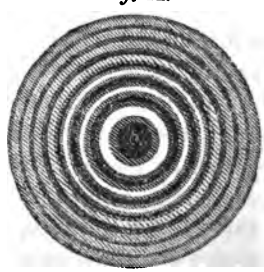
One surface of the least convex lens was placed upon the plane surface of the other, and brought together by means of three sets of screws attached to the edges, as shown in Fig. 11. In this way, between the two lenses, plane on one side and spherically concave, with a radius of 50 feet, on the other, a film of air was inclosed, without any thickness at all where the two lenses touched each

Fig. 11.

other. Figure 13 shows the two lenses in section, the curves of the lenses being exaggerated in order to show the gradual increase in the thickness of the film of air.

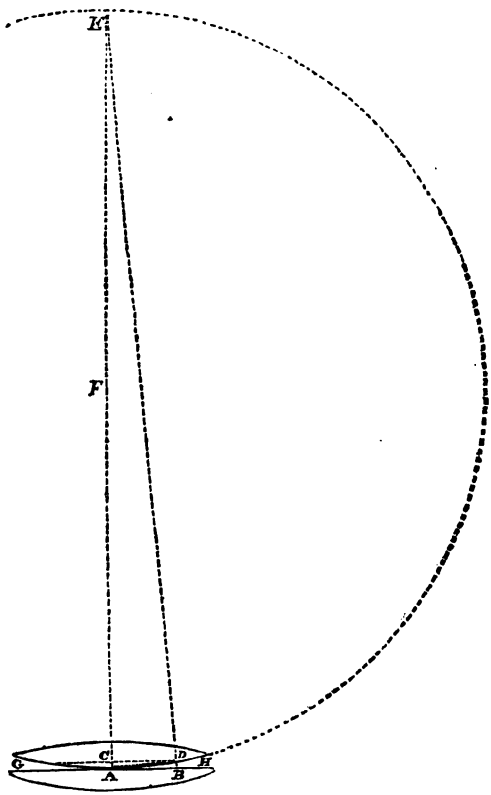
On looking down upon these lenses in the natural light of day a number of coloured concentric rings are observed, as in Fig. 11. The centre or commencement of the series where the lenses are in contact, forms a deep black spot, which is surrounded by rings of pale blue, white, yellow, orange, and deep red: this completes the first series, or alternation of colours. The second (proceeding outwards) consists of violet, indigo, blue, greenish white, yellow, orange, bright red, and crimson red. The third ring, or alternation, consists of rings of purple, indigo, blue, green, yellow, and red. The fourth series presents rings of purple, bluish green, grass green, yellowish green and red. The fifth and sixth rings, each greenish blue and pale red; and the seventh very pale greenish blue, and reddish white. Figure 12 will give some idea of the appearance of these rings seen from above; the circularity of the rings leading us to infer both the regularity of the glass surfaces, and the constant correspondence of a certain colour with a certain thickness; while the peculiar and beautiful law of decrease in the breadth of the successive alternations (which is such as to make the *area* of each bright ring, measuring from the darkest part of one alternation to the darkest part of the next, equal) leads us to certain very simple numerical relations between the thicknesses that produce the same colour in each of the different alternations, or *orders* of colours, as they are called.

Fig. 12.



Now to ascertain the thickness of the film of air between the two glass lenses, let G H, Fig. 13, represent

Fig. 13.



this film, and let the radius A F of its concave surface be 50 feet. Suppose now that it be required to find the thickness B D of a ring whose radius is A B. This radius is found by measuring from the centre A, or the black spot in figure 12, to one of the rings of colour; and we will suppose this radius to be one quarter of an inch. By drawing the chords A D, D E we get a right-

angled triangle; because every triangle within a semicircle, if the apex touch the arc and one of the sides be the diameter, is a right-angled triangle, and the angle at the apex is the right-angle.—(Euclid, b. iii. prop. 31.) In like manner we shall obtain two other right-angled triangles, A C D and E C D, by drawing the line C D perpendicular to A E, and therefore parallel and equal to A B.

The two triangles A C D and C D E are similar, and hence the ratio existing between the sides of one triangle corresponds with the ratio existing between the sides of the other. In one figure, therefore, the line C E bears the same proportion to C D, as C D does to C A or to D B, which is the thickness required. But as A C is exceedingly small compared with A E, A C may be accounted as nothing, and therefore A E and C E are, for all practical purposes, the same. So that as A E or C E is to C D, so is C D to C A or B D; or as 100 feet : $\frac{1}{4}$ in. :: $\frac{1}{4}$ in. : $\frac{1}{19200}$th of an inch, the thickness of the film of air at B D.

It will be remembered that in order to make our figure intelligible, it has been necessary to exaggerate the curved surface G H, the radius of its curvature, or A F, being hardly two inches instead of 50 feet. It will be readily perceived that the greater the circle, of which A E is the diameter, the less will be the minute distance, B D.

It would be impossible here to give an idea of the importance of these wonderful measurements; but this experiment may be said to have laid the foundation of *Physical Optics*, or our knowledge of the properties peculiar to rays of light. We must observe, however, that when the space between these lenses is filled with water, or any other liquid, instead of air, the rings, without undergoing any other change, are diminished in size, showing that a less thickness is necessary to produce any given colour of the above scale in a film of liquid

than in one of air; but that the *proportion* between the thicknesses, that produce the different tints, is the same in one substance as in any other. In this way Newton proved that when a soap bubble becomes sufficiently thin to exhibit the *black* of the first order of colours, the thickness of that part which appears black is less than three-eighths of a millionth of an inch.

26. These examples will illustrate the next *general* property of matter after its extent and impenetrability, namely, its *divisibility* into smaller parts, the limit of which has not yet been ascertained. It is extremely probable, however, from certain chemical facts, that all bodies are composed of elementary parts, which are indivisible and unalterable; these are called *atoms**. Nothing is known of their absolute size, except that it cannot possibly exceed certain magnitudes which we may calculate, but of whose extreme minuteness we can form no adequate idea. For example, we have just seen that a film of soapy water will, if carefully protected from all disturbance, hold together until it has been reduced by draining to the thickness of less than a 2,600,000th of an inch. Pure water will not hold together in this way; but the admixture of less than the hundredth of its bulk of soap will confer this property on the whole of the water. Now, in order to produce this effect, it is evident that there must be a portion of soap (at least *one* atom) in every cubic 2,600,000th of an inch of the solution. But the soap, when dry, occupies less than a hundredth of the bulk of the solution. Therefore a single atom of soap, in the solid state, cannot possibly occupy so much as the hundredth of a cubic, 2,600,000th of an inch; that is, not so much as a 1757 trillionth (1,757,600,000,000,000,000,000th) of a cubic inch.

* *Atom*, indivisible, from *α*, *not*, and *τεμνομαι*, *to be cut.*

Dr. Thomson has shown that a portion of lead may be rendered *visible*, the bulk of which cannot exceed the 888,492,000,000,000th of a cubic inch. He dissolved one grain of dry nitrate of lead in 500,000 grains of water, and after having agitated the solution, passed through it a current of sulphuretted hydrogen gas. The whole liquid became sensibly discoloured. Now we may consider a drop of water to weigh about a grain, and a drop may be easily spread out so as to cover a square inch of surface. Under an ordinary microscope the millionth part of a square inch may be distinguished by the eye. The water, therefore, could be divided into 500,000,000,000 parts, every one of which contained some lead united to sulphur. But the lead in a grain of nitrate of lead weighs only 0.62 of a grain. It is obvious, therefore, that an atom of lead cannot weigh more than $\frac{1}{510,000,000,000}$th of a grain, while the atom of sulphur (for the lead was in combination with sulphur, which rendered it visible) cannot weigh more than $\frac{1}{2,015,000,000,000}$th of a grain.

The size of those very minute quantities of matter can also be computed. Thus the bulk of the portion of lead rendered visible by the above process is only $\frac{1}{888,492,000,000,000}$th of a cubic inch.

There are many interesting examples in the useful arts of the minute subdivision of matter. Gold leaf is only the 290,636th of an inch in thickness, and it would require at least 1500 such leaves placed upon one another to equal the thickness of the paper upon which this book is printed. It is easy to trace the process by which this extraordinary tenuity is arrived at. For example: an ounce of gold is equal in bulk to a cube, each of whose edges measures $\frac{5}{12}$ths of an inch, so that placed upon the table it would cover little more than a sixth of a square inch of its surface, and stand $\frac{5}{12}$ths

of an inch in height. The gold beater hammers out this cube of gold until it covers 146 square feet. Now it can easily be calculated that to be thus extended from a surface of $\frac{5}{12}$ths of an inch square, to one of 146 square feet, its thickness must be reduced from $\frac{5}{12}$ths of an inch to the 290,636th part of an inch.

But gold furnishes a still more remarkable instance of the extension and consequent divisibility of matter. The gilt wire used in embroidery is formed by extending gold over a surface of silver. A silver rod, about two feet long and an inch and a half in diameter, weighing nearly 20 pounds, is coated with about 800 grains of pure gold. This rod is then drawn through a series of holes, gradually diminishing until it is stretched to the length of 240 miles, whereby the gold has become attenuated 800 times, each grain being capable of covering a surface of 9600 square inches. This wire is now flatted, the golden film suffering a farther extension, and having its thickness reduced to the four or five millionth part of an inch.

In the organic kingdoms the microscope has proved the existence of animals so minute that a million of them does not exceed the bulk of a grain of sand, and yet each of these creatures is composed of organs of nutrition and locomotion, as in the larger animals. The dust of the lycoperdon, or puff-ball, appears under the microscope of an orange colour, perfectly rounded, and not exceeding the fiftieth part of a hair's breadth in diameter; so that if a globe of any substance were taken, having the diameter of a hair, it would be 125,000 times as great as the seed of the lycoperdon.

One hundred yards of raw silk weigh less than a grain, and a 3000th of a yard, or a 300,000th of a grain can be handled and examined with the naked eye. The thread spun by the common spider is much finer than that of

the silk-worm, and there are spiders 1000 of which would not make up the bulk of a common spider. Their threads are invisible except when reflecting the direct solar light, and yet it is found by the microsope that every spider has about 4000 spinnerets, each producing a separate thread, all of which are united into one bundle to form what we call a gossamer thread.

Thus, as far as observation has extended, it appears that however minute a body may be, it is still capable of further division; that is, science has not succeeded in discovering a limit to the divisibility of any one kind of matter; and yet chemical facts render it almost certain that such a limit exists in *every* kind of matter.

27. Atoms of matter are held together by an attractive force called *cohesion*, which is greatest in solids, less in liquids, while in aeriform bodies it appears to be altogether absent.

The atoms of matter cannot be in actual contact since every kind of matter is more or less capable of compression. Heat is supposed to be the antagonist of cohesion, but however this may be, there seems to be some repulsive property which prevents atoms or molecules from touching each other. The spaces between them are called *pores*.

Porosity is a universal property of matter. It is not confined merely to animal and vegetable structures, but is found in every substance that has been examined. A thin slice of the hardest wood examined under the microscope is found to be full of holes or pores, beautifully arranged. A lump of marble, granite, or other compact stone, plunged under water and placed under the receiver of an air-pump will, on withdrawing the atmospheric pressure, expel a torrent of air-bubbles, which had been concealed in the internal pores of the stone. There is a kind of agate, called *hydrophane*,

which, in its ordinary state, is only semi-transparent; but, after being plunged in water, it takes up about one-sixth of its bulk of that fluid, and becomes nearly as transparent as glass.

The porosity of metals was proved in the year 1661, by the celebrated Florentine experiment. The Academicians del Cimento submitted a hollow ball of gold filled with water to a great pressure, by which the water was made to ooze through the pores in the surface of the gold. This experiment has often been repeated with different metals with the same success.

Although the porosity of glass and many other bodies does not admit of this proof, yet it is rendered quite evident from their expansion by heat and contraction by cold. We may observe that, on the whole, the greatest philosophers have all concurred in the belief that the atoms even of the densest solids are very much smaller than the spaces which separate them. Newton even supposed them *infinitely* smaller; or, in other words, regarded them as mere mathematical *points;* or, as Boscovich expressed it, moveable *centres* of attractive and repulsive forces. There are some phenomena, however, which seem to indicate that they have definite forms, and therefore definite sizes. Yet Sir John Herschel asks why the atoms of a solid may not be imagined to be as thinly distributed through the space it occupies, as the stars that compose a nebula; and compares a ray of light penetrating glass, to a bird threading the mazes of a forest.

28. The porosity of matter leads us next to consider another universal property, which is a necessary consequence of it. All known bodies can be reduced, by pressure, into smaller limits; that is, their *volume* can be diminished without diminishing their *mass* or quantity of matter. This property is called *compressibility,*

and numerous familiar examples of it will readily occur to the reader. We will give a few which are not so obvious.

If a bottle of fresh water be corked up and sunk to a great depth in the sea, the cork will be compressed and driven into the bottle, so as to allow the salt water to mingle with the fresh. On drawing up the bottle the cork will expand to its original dimensions, and again occupy its place in the neck: so that it is necessary to taste the water to be convinced that the cork has been disturbed. Pieces of oak, ash, or elm, plunged into the sea to the depth of 1000 fathoms, and drawn up after two or three hours, have been found to contain four-fifths of their weight of water, and to acquire such an increase of density as to indicate the contraction of the wood into about half its previous volume, so that if thrown into a pail of water they sink like a stone.

Some of the metals have their bulk permanently diminished by hammering. When metals are melted together in the formation of alloys there is often a great contraction. Equal bulks of tin and copper are found to undergo a contraction amounting to the fifteenth part of their whole volume.

It was long supposed that liquids were incompressible, and the Florentine experiment was urged as a proof of the assertion. Canton was the first to prove them compressible, and Oersted has invented a beautiful form of apparatus, by which it was proved that for every additional *atmosphere* (as it is called, or pressure of 15 lbs. on the square inch), water was compressed rather more than 46 millionths of its volume; alcohol, 21; and ether, 61 millionths of their respective volumes.

Aeriform bodies are those which are best adapted to exhibit the property of compressibility. If we take a

metal cylinder, closed at one end, and insert an accurately fitting piston into the other, it will be found impossible to force the piston into the tube if it be full of water; but, if full of air, the force of the arm is sufficient to drive the piston down so as to reduce the volume of air ten or twenty times, if the piston be small. We feel the resistance increase in proportion to the compression; and, whatever force is exerted, we cannot make the piston touch the bottom of the tube, because in order to do that the air must lose its impenetrability, or, in other words, be annihilated. When the pressure is removed, the air regains its original bulk, which is not the case with metals and some other solids after they have been strongly compressed.

29. The force with which most solids and all fluids tend to expand when compressed, is one variety of *elasticity*, another property common to all matter, and which, in its widest sense, is applied to the tendency its particles have to preserve a certain *distance* or *position* with regard to each other, and resume that distance or position when disturbed therefrom. In *fluids* this applies only to the *distance* and not the *position* of the particles; for they have no tendency to assume one position in preference to another. This tendency is the peculiar characteristic of *solids;* in which we accordingly distinguish not only the elasticity of *compression* (common to all bodies), but also three other kinds of elasticity not found in fluids, viz., those of *tension*, *flexure*, and *torsion;* for the various ways in which we can alter the form or dimensions of a body, may all be reduced to these four modes, *squeezing*, *stretching*, *bending*, and *twisting;* but only the first of these is applicable to fluids.

In no solid, however, is any one of these four kinds of elasticity found to be both perfect and unlimited. In

some solids, such as glass, they all appear to be *perfect*, for no force, however great or long continued, causes glass to take a *set*, as it is called, that is, a permanent change either in form or bulk; but then this elasticity is confined within narrow limits, on exceeding which, *fracture* is the result. In those solids whose elasticity (of one or more kinds) is less limited, as in metals, or apparently unlimited (as in the flexure of Indian-rubber, or the torsion of a thread), the return of the particles to their previous position is only partial. There remains a permanent change of form, which is called a *set;* as in the compression of metals we have seen that there is a permanent change of bulk.

In fluids, however, although three of these kinds of elasticity, viz., those which relate to the position of the particles, are wanting; yet the remaining kind, that which relates only to their distance, is at once *perfect* (like the elasticity of glass), and apparently *unlimited* in extent.

30. We have thus briefly considered those properties which are common to all matter when in a state of *rest;* or those which relate only to *space*, and require no regard to be paid to the element of *time;* and it will be observed that none of these properties affords the means of measuring *mass* or quantity of matter; for none of them is invariably the same in the same body, so as to enable us to compare two bodies and ascertain their ratio, as two *magnitudes* or *quantities*. The compressibility of matter proves that the volume of a body, or the magnitude of space, is altogether independent of the magnitude of matter, since the former may vary while the latter remains constant; and we have really no means of comparing quantities of matter till we introduce the considerations of *time*, *motion*, and *force*.

The science of general mechanics (as distinguished from *solid* mechanics) has for its object the study of the action of forces upon matter. Mechanical forces may be considered as motions actually produced, or tending to be produced*, without any reference to the nature of the force or its generating cause. Hence two forces which impart to the same body the same degree of speed in the same direction, are regarded as identical, whether they originate from animal power, a weight descending by its gravity, the impact of a heavy body, or the elasticity of steam, &c. Mechanics resolves the action of these forces into problems, and considers the effect produced upon a given body by different forces acting together, when the simple motion produced by one of them is known; or, inversely, this science determines what combination of simple forces will produce an observed compound motion. Hence the peculiar province of mechanics is the study of the combination of forces, whether by their united action a motion is produced, the different circumstances of which are to be studied, or by the mutual neutralization of these forces the body is brought to a state of equilibrium, the conditions of which have to be fixed by *Statics*. This last named branch, however, is always studied first, being by far the simpler of the two, because the element of *time* is excluded.

31. The laws of motion are frequently cited as illustrations of the *inertia* of matter, a term which is in

* But whatever is capable of opposing and neutralizing another force, so as to produce *equilibrium*, must itself be regarded as a force, even though it have no tendency to produce motion. This is the case with *friction* and those other retarding causes, which never acting as producers or accelerators of motion are therefore called *passive* forces, or *resistances*.

many respects an unfortunate one, since it supposes matter to be by its nature essentially inert or passive, and that it is never active except under the influence of external forces. The supposed natural and inherent inertness of matter is expressed by the term *vis inertiæ*, or *force of inactivity*, a contradiction of terms, which, however, is only apparent, force being the cause, and motion the effect produced by it on matter; so that, to say that matter is inert or has *inertia*, is only to say that the cause is expended in producing its effect, and that the same cause cannot (without renewal) produce double or triple its own proper effect.

Inertia, however, must not be regarded as a *sluggishness* or tendency to rest rather than motion*; but as a total indifference to either of these states, or a tendency to resist all *change*, either a change from rest to motion, or from motion to rest, or a change in the intensity of motion (either by increase or diminution) or a change in its direction. Hence it has been proposed to replace the objectionable term *inertia* by the term *persistence*, implying the tendency of matter to preserve its present state, either of rest or motion, unchanged; or, in other words, the necessity of *force* to produce change of any kind, either in the *velocity* of motion or in its *direction*.

That matter itself, however, is capable of exerting this force and of producing these changes, either in itself or in other matter, is obvious from every motion in the heavens or the earth. By the action of the

* That matter set in motion has in itself a tendency to be retarded and finally to *stop*, unless fresh force be constantly supplied to maintain the motion, is a vulgar error, which must be discarded before we can apply any exact reasoning to the phenomena of motion. All *change* in motion being regarded as the effect of some exertion of force; whenever retardation is observed, it must be referred to some opposing force, without which the motion would continue indefinitely.

matter of the earth on that of a projectile, the *velocity* of the latter is changed every moment, diminished while it is rising, and increased during its descent; and, unless the motion be vertical, its *direction* also is changing continually like that of the heavenly bodies; thus, showing that the force which produces these changes, both in velocity and direction, is exerted unceasingly, as well as universally, by all matter. The same remark applies to the various forces, attractive and repulsive (incomparably more powerful than gravitation), by the balance of which, the particles of solids are held together, yet prevented from touching (27), and kept at certain distances and in certain positions, which it requires enormous force to disturb, even to an inconceivably small extent. So, also, in a vast number of thermological, electrical, and chemical phenomena, matter exhibits varied forms of spontaneous activity, making it quite impossible to attach the meaning which is commonly given to the term inertia.

32. The first law of motion, discovered by Kepler, has been called the *law of inertia.* It states, as a general fact, that all motion is *naturally* rectilinear and uniform; that is to say, a body submitted to the action of any single force acting instantaneously, *must* move constantly in a straight line with invariable velocity, unless it be compelled to change that state by forces impressed upon it.

33. The second fundamental law of motion is due to Newton. It relates to the constant and necessary equality between action and reaction; that is to say, that whenever one body is set in motion by another body, the first reacts upon the second in a contrary direction, and the second body loses a quantity of motion exactly equal to that which the first has received. By *quantity of motion,* however, (otherwise called momentum or moving force) we must not under-

stand *velocity*. This is only the *intensity* of motion, not its *quantity;* for the quantity of any effect is to be estimated *jointly* by its intensity and by the quantity of matter which is affected with that intensity. If the intensity of the effect remain constant, its quantity must always be proportional to the quantity of matter affected; and, supposing this latter to remain constant, the quantity of effect is proportional to its intensity *. The momentum or quantity of motion then, in two equal bodies, is proportional to their velocities; but in two equally swift bodies, it is proportional to their *masses* or quantities of matter; and when they are neither equal nor equally swift, it is jointly proportional to the masses and the velocities, or proportional to the *product* of these two quantities.

Hence we see that the phenomena of motion afford a means, and the *only* means, of comparing *masses* or quantities of matter. For this purpose we must start from the fundamental truth above mentioned; that in every action (that is, every change from rest to motion, or from motion to rest, or change in the velocity or direction of a body's motion) there is an equal and opposite effect produced on some other body or bodies, —an *equal* effect, not as regards intensity, but quantity. Knowing, therefore, the *quantities* of these two opposite effects to be equal, and observing the relation between their intensities, we learn from this the relation between the quantities of matter affected, which must necessarily be inversely proportional to the intensities of the two effects †.

* This maxim is applicable alike to every effect producible on matter; not only motion, but any of those effects which (though conjectured to be only particular kinds of motion) are in the present state of science necessarily regarded as distinct agencies; such as heat, light, electricity, and magnetism.

† This is all that is meant when *inertia* is spoken of as a *property*

34. The third fundamental law of motion, discovered by Galileo, leads us to notice briefly what is called the *composition of forces*, by which is meant, that a body acted on by two or more forces at once for a given time, will be carried to the same spot to which it would eventually have been brought by the separate and successive actions of these forces, each for the same length of time that they were supposed to act together. Hence, any two forces may be *compounded*, or a new force substituted which shall be exactly equivalent to them, for if lines proportional to them be made the sides of a *parallelogram*, its *diagonal* will, both in direction and length, represent their *resultant* or compounded force; and, conversely, any force may be *resolved* into two or more forces, together equivalent to it, and having any directions required.

In considering the action of several forces in different planes, it is found extremely convenient to resolve each of them into three portions, acting in *three* fixed directions, all at right angles to each other, as 1, north and south; 2, east and west; and, 3, up and down. But, in considering forces in only one plane, it is suffi-

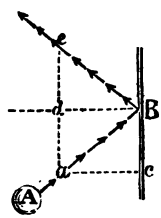
common to all matter, and is said to be proportional to its mass; for, in fact, this so-called property is the only measure we can have of the quantity of matter. *Weight*, indeed, is generally taken as synonymous with mass or quantity of matter; but this is not true, for the same mass which weighs a pound in London would not weigh three ounces on the surface of the moon, and it would weigh nearly three pounds in Jupiter. It would even weigh less than a pound at Brighton, and more than a pound at Manchester; but, of course, the difference could not be found by comparing weight with weight, in a balance, because both weights are increased or diminished alike. To detect the difference of weight, it must be opposed to some other force, such as the elasticity of a spring. Two clocks, one driven by a weight and the other by a spring, and keeping equal time at any place, will no longer preserve this equality when both are removed to a different latitude, or a different elevation above the sea level.

cient to resolve each into *two* directions, one parallel and the other perpendicular to some remarkable object or force.

For examples of these laws and of these methods, the reader is referred to the treatises on elementary mechanics and engineering; but we must here mention one very simple example of the application of them all.

35. The direction of the reflexion, or rebound of a moving body from a fixed obstacle (a billiard ball from the side of the table for instance), will afford an illustration of all the laws of motion, and of the use of its resolution and recomposition. Let a ball roll along the line A B, Fig. 14, so as to strike the ledge obliquely at B. Its moving force may be resolved into two equivalent forces, one parallel to the ledge, and the other perpendicular thereto. Let *a* B be the space described by the ball in an unit of time, then *a c* and *a d* will be the spaces it would describe by the action of these two forces separately, each during an equal unit of time.

Fig. 14.



Now, if the latter force acted alone, it is plain that the ball would exert no action on the ledge, consequently this force adds nothing to the blow, which depends solely on the other resolved portion of the whole force, viz., that portion perpendicular to the ledge. The blow is precisely the same as if the ball rolled along *d* B in an unit of time. It acts then on the ledge with a certain force in the direction *d* B, and the ledge accordingly (by the second law of motion) reacts on the ball, with an exactly *equal* force, in the contrary direction B *d*, and would therefore send it in an unit of time to *d*. But, meanwhile, the other resolved portion of the whole force, viz., that

portion parallel with the ledge, remains unaltered either in intensity or direction, and as it would, in an unit of time, have sent the ball through the space *a d*, so it would in another unit, send it through the space *d e*. This motion must therefore be compounded (by the third law of motion), with the reaction of the ledge which would carry it, in the same unit, through B *d*, and thus we shall find that it will, in this second unit, describe the line B *e*, which evidently makes the same angle with the ledge, as did the ball's original path A B. This is commonly expressed by saying that the angle of *incidence* is equal to the angle of *reflexion;* the former meaning the angle A B *d*, and the latter *d* B *e;* and though this law is only approximately true of moving bodies (owing to the resistances arising from their imperfect elasticity and other causes which render the reaction *apparently* not equal to the action), yet we shall presently see that it applies *strictly* to the motions of sound, heat, and light, and is therefore of the utmost importance throughout physics.

36. There is a consideration connected with the third law of motion which is important to be noticed, namely, that a motion common to all the bodies of any system does not at all interfere with the particular and individual motions of this system. These motions may be carried on with as much facility as if the system was at rest. For example, if a ship be sailing ever so rapidly on a calm river, a stone dropped from the mast-head will fall on precisely the same spot of the deck as if the ship were stationary. It falls in a diagonal line, its motion being compounded of the vertical descent produced by gravity, and the horizontal motion common to every object in the ship. So, also, a watch may be carried with great rapidity without interfering with the complicated movements of its works; or an animal

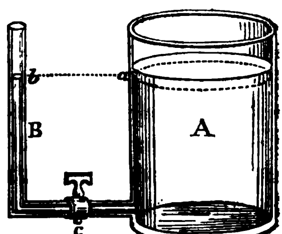
may walk or run, or fly or swim, without interfering with the motions of circulation and respiration; and the earth on which we live spins round upon its axis from west to east, at the rate of 1042 miles an hour (at the equator), without interfering with the various complicated motions upon its surface, except in modifying the direction of the trade winds and a few other similar effects, which result from the strict application of this law. Suppose, for example, a bullet dropped from the centre of the lantern of St. Paul's, it would not fall on the point to which a plumb line would hang therefrom, but nearly an inch to the *east* of that point. The reason is this. During the fall (which would occupy about 4½ seconds), the building would be carried eastward, by the earth's axial rotation, through a space of about three quarters of a mile; and, by her orbitual motion, through nearly ninety miles. It is only the former motion, however, which causes this effect, for if the building only advanced in a *straight line*, however fast, the stone would fall as it does from the mast-head of the ship above mentioned. But by the motion of *rotation*, it is plain that the top of the building describes daily a rather larger circle, and therefore moves rather faster than its base. Now, the bullet, during its fall, retains the same forward speed which it had at the top of the building, and is therefore *in advance* of the slower moving surface on which it falls, by a minute space, which, however, has been measured by delicate experiments.

37. The essential principles of statics and dynamics apply equally to fluids and solids, except that in respect of fluids there are certain peculiar conditions, such as the property which gives them a name, viz., fluidity, fluid pressure in all directions, &c., which render problems in hydrostatics and hydraulics

more complicated than those which relate to solids only.

It is not easy, in ordinary observation, to realize the idea of fluid pressure equal in all directions, since our general experience of the weight of a body is simply downwards. But the difficulty will disappear when we consider that we speak only of the equality of pressure in all directions, at any *one point* in the fluid. That each point or particle must be pressed equally above, below, and on all sides, is plain from its remaining at rest; for if there were an excess of pressure in any direction, it must move in that direction, till it arrives at a place where the surrounding pressures are all equal. This equality of pressure in all directions, at any point in a fluid (in equilibrium), is the fundamental principle from which all the reasonings of hydrostatics are to be deduced; and it is the direct consequence of that mobility of particles; that absence of any tendency to preserve a particular position with regard to each other; which we call *fluidity*. The particles glide over each other with perfect freedom, each particle pressing equally on all the particles that surround it, and is equally pressed upon by these; it also presses equally upon the solid bodies which it touches, and is equally pressed upon by these. From this property, conjointly with the gravity of the particles, it follows that when a fluid is left to itself, all its parts rise or fall, so as to settle at the same level. Thus, if a large vessel A, Fig. 15, be filled with water, and made to communicate with a small vessel B, the connecting tube being furnished with a stop-cock *c*, on opening the

Fig. 15.



latter the water will rise up and fill the small tube, and when the motion has subsided, both will be found to settle on the same horizontal line, *a b;* the water in A will sink a little, say to the dotted line, and will rise in *b* to the same line.

38. The principle of fluid pressure, as illustrated by water not rising above its own level, is subject to some modification by the *attraction of adhesion,* a force which refers to the physical attraction of the particles of dissimilar bodies in contradistinction to the force of cohesion, which is the attraction between the particles of the same body. On plunging a body into water, it comes out wet; that is, a portion of water *adheres* to it. Now this attraction between the particles of a fluid and those of a solid is supposed to be similar in *kind*, but different in *intensity*, to the cohesive force which binds together the particles of the fluid.

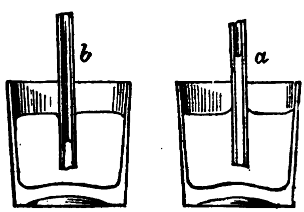
This adhesive attraction may be shown by suspending from one arm of a balance a thin plate of any substance over a vessel of water. As soon as the plate touches the water, it will require a considerable weight in the opposite scale to separate the plate from the water. This weight has been taken to represent the force of adhesion, and by using plates of different substances, but of the same area, different weights are required to separate them from the water. In this way, tables of adhesion have been formed for different substances; but it must be borne in mind that in separating the plate from the water, a film of that fluid is torn away, and that the cohesive attraction of the particles of the film for the rest of the fluid has first to be overcome. Hence the numbers which represent the adhesive attraction of different substances found in this way are probably all too high.

39. If tubes of very fine bore have their ends immersed in water, the water will ascend in them to a

certain height, which is great in proportion to the narrowness of the bore of the tube. Such tubes are called *capillary*, from their bore, being not much thicker than a *hair*, and this form of adhesion is called *capillary attraction*. Examples of it are very numerous, such as the ascent of water in a piece of lump sugar, the pores of the sugar acting as capillary tubes; the ascent of oil in a lamp, the cotton fibres serving also as fine tubes. Sap ascends in plants by the same force, and some idea of its intensity may be gained by fitting a dry plug of wood tightly into a stout tube of glass or porcelain. If a projecting portion of the wood be allowed just to dip into water, the liquid will ascend and cause the wood to swell with such force as to burst the tube, although capable of resisting a pressure of more than 700 lbs. on the square inch.

On placing the extremity of a capillary tube in a vessel of water or spirits of wine, the liquid will ascend in the tube above the level of that in the vessel, and the surface of the little column thus suspended will be a hollow hemisphere, as shown in Fig. 16 *a*. If the same tube be plunged into mercury, the liquid in the tube, instead of rising *above*, will be depressed *below* the general surface, as shown in *b*. The surface of the mercury in the tube will be convex instead of concave. The same effect will take place when capillary tubes are plunged in water, provided the water cannot wet the tubes, as when they are covered within with a thin film of oil, which prevents the adhesion.

Fig. 16.



The phenomena of capillary attraction and repul-

sion may also be seen in vessels containing fluids. If the fluid is capable of wetting the sides of the vessel which contains it, it will be raised and become concave all round the sides, as may be seen in a glass of wine or a cup of tea, and as shown in Fig. *a*; but if the glass or cup be too full, the absence of lateral attraction by the vessel, and the predominance of the force of cohesion from within, will give the liquid a rounded form. If the vessel cannot be wetted by the fluid, as when it is greasy, or mercury be used, the fluid will be depressed all round the vessel and have a convex surface, as in Fig. *b*. Some curious appearances of attraction and repulsion are produced by the operation of *capillarity* (under which term all effects depending on the adhesion of fluids to solids are now included). Two balls of pith or wood, either both dry or both wet, floating in water, attract each other when so near together that it matters not whether the surface be raised or depressed where it approaches them; but if one ball be wet and the other dry, they repel each other as soon as the liquid surface which separates them is curved. All these effects have been made the subjects of deductive science, and with great success. They have been generalized by Clairaut into the following law. If the *intensity* of the attraction of the solid on the fluid be *greater* than *half* that of the fluid on itself, the fluid will *elevate* itself above the solid; if it be *less*, it will *depress* itself; and if it be *equal*, it will neither elevate nor depress itself.

40. Water affords a very useful means of comparing the *specific gravities* or densities of bodies. To understand this, we must remember that bodies placed under the same circumstances, or attracted by the same body and at the same distance from it*, gravi-

* The same distance from its *centre of mass*, or *centre of gravity*, as it is likewise called, and not from its surface.

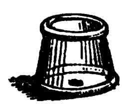
tate thereto with forces proportional to their masses; so that the *weights* of bodies at the same spot on the earth's surface are proportional to their *masses* (as measured by inertia). The simplicity and generality of this fact causes it to be often passed by as too evident to need demonstration, whereas it is by no means self-evident, but a matter of very nice experiment and observation. For this purpose, Newton made a hollow pendulum, in the bob of which he enclosed successively equal weights of various substances, as metals, stones, woods, &c. Now, if these equal weights had been unequal in mass, (or inertia,) they would not have caused the pendulum to oscillate (as it did) always with the same rapidity. It is a consequence of this law, that all bodies, whether light or heavy, fall (at the same place, and abstracting the resistance of the air) with the same velocity, as shown in the well-known experiment of the guinea and feather in vacuo. But the best proof of this very simple law is obtained from the heavenly bodies; for, if all the planets did not weigh sunward with weights proportional to their masses, (after allowing for their different distances,) their periods would not be as the square roots of the cubes of their mean distances, which is well known to be one of the invariable laws discovered by Kepler. Now, this proof of the proportionality of weight to mass is the more remarkable, because the masses of these bodies are very far from proportional to their bulks. Thus the sun is 1,333,000 times *larger* than the earth, but only 354,936 times *heavier;* whence it follows, that he is little more than a quarter so *dense;* and the densities of the planets differ prodigiously, Mercury being nearly as dense as gold, while Saturn has hardly half the density of water.

The mode of comparing the densities of ter-

restrial bodies has been given in Rudimentary Chemistry.

41. The equality of fluid pressure, as noticed in liquids, is also one of the most striking and beautiful properties of the atmosphere. It has already been shown (11) that a column of mercury, 30 inches high, whose horizontal section is equal to a square inch, represents the weight or pressure of a column of the atmosphere resting on a square inch and extending upwards to the limits of the atmosphere in space, a height which has been calculated at about 45 miles. Now, as a column of mercury such as we have described weighs 14½ pounds, and the atmospheric column balances this pressure, it follows that all beings and objects situated at the bottom of our aerial ocean experience a pressure of 14½ pounds on every square inch of surface. The body of a man of ordinary stature undergoes a pressure of no less than fifteen tons from this source, and the reason why he is not inconvenienced by this enormous force is the equality of its pressure, both without and within all the minute vessels of which every organic structure is composed. A sponge plunged to the depth of 33 feet in water bears double the atmospheric pressure, and at 1000 feet deep about 30 times that pressure; yet its most delicate structure is not injured, nor its motions impeded. We become painfully sensible of the atmospheric pressure on removing any part of it from the surface of the body. For example, if we place the broad end of a stout glass, Fig. 17, open at both ends upon the table of an air-pump, and close the upper end with the palm of the hand, and then remove some air from the glass, the hand is held down by the weight of the atmosphere, and the effect is painful if the vacuum is tolerably perfect.

Fig. 17.

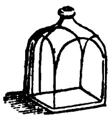


The pressure of the air is a consequence of its weight, 100 cubic inches at the temperature of 60°, and when the barometer stands at 30 inches, weighing nearly 31 grains. Any causes which tend to depress the barometer, while the temperature remains constant, will of course diminish the weight of a given volume of air. At the height of 18,000 feet above the level of the sea the barometer would stand at 15 inches, because we should then have ascended above half the atmosphere. At the height of seven miles the mercury would stand at 7½ inches, when there would be still one quarter of the atmosphere at a higher elevation, because its upper parts having less weight to bear expand into far greater space. Rare as the air in which we live appears to be in comparison with liquids or solids (for the air is more than 800 times rarer than water), this habitable stratum must yet be regarded as enormously *compressed* by having to bear the whole mass of the atmosphere above it, for from the sea level to an elevation of 3½ miles there is as much air as in the remaining 41 or 42 miles to which the atmosphere is supposed to extend.

A barometer situated at one spot on the earth's surface is liable to variations in its height. In our own country the mercurial column oscillates between about 28·3 and 30·8 inches, the causes for which will be studied in our treatise on Pneumatics.

42. The elasticity of the air arising from the repulsive force of its particles is necessarily equal to the compressing force which it balances. Thus, any confined portion of air exerts against the whole inner surface of the containing vessel, exactly the same pressure which an equal surface would receive from the weight of the external atmosphere, if exposed thereto, namely, a pressure of 14½ lbs. on every square inch.

Fig. 18.



If a glass vessel, Fig. 18, with square sides, full of air, be sealed up, and put under the receiver of an air pump, the elastic force of the enclosed air will burst the vessel to atoms when the pressure is removed. The external pressure of the air exactly balances the inward pressure, so that on removing the former the latter acts with full effect.

43. The air is the medium by which sound is propagated to our ears. We have already (15) given some general notions of the mode of its propagation, and shall enter further into the subject in "Rudimentary Pneumatics." It is necessary, however, in this place, to notice a few particulars respecting the laws of sound, for the purpose of illustrating some remarkable facts respecting *light*, which will presently be considered.

The motion of sound through the air is at the rate of about 1125 feet per second at the temperature of 62°. At the freezing temperature, when the air is denser, it is only 1089¾ feet per second. The method of determining this velocity is to watch the time that elapses between the flash and the report of a gun fired at the distance of several miles from the observer. As light travels at the rate of nearly 200,000 miles per second, its passage occupies a portion of time too small to be measured in any terrestrial distance. It may therefore be supposed to be seen at the distance of several miles from the observer at the very instant of its production. If, therefore, an observer at one station begin to count seconds on an accurate dial, the moment he sees the flash of a gun at another station, say ten miles off, the number of seconds and fractions of a second which elapse between seeing the flash and hearing the report will give a divisor for the number of feet between the

two stations, and the quotient will represent the velocity of sound in feet per second.

44. All sounds, whatever their *intensity*, whether the noise of a cannon or a whisper; whatever their *pitch*, whether from the diapason organ pipe or the chirping of a cricket, and whatever their *quality*, whether the finest music or the most grating noise, all travel with the same amount of speed.

It has been already stated (15) that when sound from whatever source is propagated in air, *waves* are formed similar in character to those which may be so beautifully studied when the wind is blowing over a field of standing corn. Now, when it is said that sound travels at the rate of 1125 feet per second, it is not meant that the particles of air move through that distance any more than the ears of corn travel from one end of the field to the other; it is only the *form of the wave* which thus travels. So with the particles of air: their individual movement is confined within narrow limits; but the effect of this movement is propagated from particle to particle with the rapidity of 1125 feet per second, which, although it would be thought very rapid for a *motion* or the *transfer of a body* (being about ten times faster than the most violent West India hurricane), is yet very slow for the *communication* or *transfer of motion;* for, if we pull or push one end of a solid rod, or the liquid filling a long tube, the other end appears to move at the same instant; and although this motion of motion must occupy time (unless the body were perfectly incompressible), it is much more rapid in these cases than in air, which, on account of its great compressibility, is one of the slowest conveyers of sound. Every one must have observed that vibration can be diffused through a long mass of metal or wood, so as to be heard at a greater distance than

through air; but in this case, if the sound be loud enough to be audible through the air also, it will be heard twice, first through the solid, and then through the air. Iron conveys sound about 17 times faster than air, woods from 17 to 11 times, and water $4\frac{1}{2}$ times faster than air.

45. When waves of sound meet any fixed surface tolerably smooth, they are reflected according to the law of equal angles of incidence and reflection already noticed (35). In this way *echoes* are produced. Between two parallel surfaces a loud sound is reflected backwards and forwards, and several echoes are audible. Six may be heard between Carlton Terrace and the Birdcage Walk, in St. James's Park, London; fourteen between the steep banks of the Avon at Clifton, and as many under Maidenhead railway bridge. When the parallel surfaces are much nearer together (as the walls of a room), although a large number of echoes are produced, they follow each other too rapidly to be distinguished; and as they reach the ear after equal intervals, they produce a musical note, however unmusical the original noise may have been. Hence all the phenomena of *reverberation*. The pitch of the note depends on the distance between the two walls which cause it, and may be calculated therefrom.

A noise may also produce a musical echo by being reflected from a large number of equidistant surfaces receding from the ear, so that the sound reflected from each may arrive successively at equal intervals. If we stamp near a long row of palisades, a shrill ringing will be heard. A fine instance of the same kind is said to occur on the steps of the great pyramid. If the distance from edge to edge of each step were 2 feet 1 inch, the note produced would be the tenor C, because each echo (having to go and return) would be 4 feet 2 inches later

than the previous one, which is the length of the waves of that note. But as the steps gradually diminish in size upwards, the echo, if produced, and heard at the bottom, must gradually rise in pitch.

46. We have thus glanced at those phenomena which have been generalized by the discovery of the laws of dynamics, or which are reducible to the single principle of motion produced in matter possessing invariably the following properties, namely, *extent*, *impenetrability*, *elasticity*, and *weight*. In our treatises on Mechanics and Pneumatics, we propose to enter more at length into these important subjects. It was necessary to reserve a considerable portion of our space for the consideration of those agencies which, although mutually convertible into, or producing and produced by, mechanical force, have not yet been brought under the dominion of mechanical laws. We have now to direct the reader's attention to *changes* in matter, which have not yet been proved to come under the general principle of *change of place;* and it has only been after much inductive reasoning that *Sound* has been proved to be a particular case of *motion*, and has thus been made a branch of mechanical science. The actions now to be considered are varieties of *force*, indeed, and the force expended is constantly found to be jointly proportional to the intensity of effect and the quantity of matter affected; but these effects have not been proved to be merely varieties of motion, although the complete reduction of all the phenomena of sound to that principle renders it probable that *Heat*, *Light*, *Magnetism*, and *Electricity* will hereafter be referred thereto with equal success.

47. The whole of the material world is under the influence of *heat*, and all scientific investigations are more or less influenced by this wonderful and myste-

rious agency. In its ordinary sense, the term *heat* is used to denote a quality otherwise called *high temperature*, the reverse of cold or *low temperature*. In a scientific sense, the term heat or *caloric* is used to denote that *substance* or *action* which, by its greater or less abundance, or intensity in matter, produces effects which are also expressed by the terms *high* or *low temperature*.

The nature of caloric being a matter of pure hypothesis, it is necessary to receive with caution the terms used in referring to it. When we speak, for example, of a *portion* of caloric as of a quantity that may be added, subtracted, multiplied, or divided, *conducted* through a body, *absorbed* by another body, and again *evolved* or *emitted*, *radiated*, *reflected*, *conveyed*, &c., these terms must be taken as convenient modes of describing facts, not as explanations of facts. All these expressions are just as applicable to a force, an action, or a motion, as to a substance. A motion of vibration, for example, may vary in intensity so as to be treated like an arithmetical quantity, and may be propagated from place to place in any of the above modes, or undergo any of the modifications implied by the above terms.

In order to render facts intelligible, we may suppose heat to consist of matter of extreme tenuity. We know that the most delicate balance is unable to detect a change of weight in a body either by the addition or subtraction of heat. The particles of this fluid (if such it be) must be endued with indefinite self-repulsive powers, and thus diffusing themselves between the atoms of other bodies, and tending to force those atoms asunder, thereby oppose and balance the force of universal attraction or gravity which tends to bring them together.

Heat may also be regarded as a vibratory or oscillat-

ing motion of each particle of matter, varying in extent and velocity, but perpetually maintained by every particle of every body in nature, and constantly tending to equalize itself by communication from particle to particle, and also from body to body, even through the greatest distances, by means of waves propagated through the *ether* or fluid which optical and astronomical facts render it probable fills all space not otherwise occupied by material atoms.

Many of the phenomena of heat are equally well described by the language of either of these hypotheses; other facts are more intelligible by one mode of viewing them rather than by the other, and some seem to require a union of both suppositions. It is not, however, necessary to attach our faith to either hypothesis in order to understand the varied and beautiful effects of heat.

48. The most familiar effects of heat are included under the general term *change of temperature*, which implies, *first*, the production of certain animal sensations known as *heat* and *cold;* but as a decrease of temperature below a certain point destroys organic life, while too great an increase of it destroys both life and organization, this test of change of temperature is confined to a comparatively small range, and is also too vague to admit of a comparison of temperatures even within this range. But change of temperature implies, *secondly*, a change in the relative intensities of the attractive and repulsive forces of the particles of all bodies, inorganic as well as organic. The tendency of all bodies, at the same temperature, is to occupy a certain amount of space; and this tendency can only be accounted for by supposing, that when they fill this space exactly, their particles are in equilibrium between at least two forces, one tending to bring them together and the other to separate them, which forces must vary

according to different functions of the distance between two particles; so that there is only one distance at which these forces can be balanced. When the particles are nearer than this, the repulsive force preponderates, and when farther apart, the attractive force is strongest. Now, a change of temperature implies a change in the rate of variation of one or both of these forces, and consequently an alteration of the distance at which they balance each other, and therefore an alteration in the amount of space which the whole body tends to occupy, or which it will occupy, if not prevented by surrounding bodies.

This may be a circuitous method of stating the well known fact, that "all bodies expand by heat and contract by cold," but this common expression does not correctly represent the fact in all its generality as applied to the solid, liquid, and gaseous states of matter; because if we take the gaseous state which is most affected by change of temperature, the gas under examination must of course be confined in a vessel of some kind, or we could not be sure of its identity. But it is the distinctive property of this kind of matter always to *fill* the vessel in which it is confined, however small the actual quantity or weight of the gas may be. If it be heated it cannot expand, for it already fills the vessel; if it be cooled it does not contract, for it still fills the vessel and presses against its inner surface even at the lowest temperature. If then it be said that this portion of matter, under these circumstances, expands by heat and contracts by cold, such is not the case, for it always maintains the same bulk. If it be said that it *tends* to expand by heat and to contract by cold, such is also not the case, because it always tends to expand, as is proved by its always pressing against the whole interior of the vessel. All that can be said

in strictness is, that change of temperature alters the relation between the attractive and repulsive forces of its particles, and, therefore, alters the distance at which those particles would remain in equilibrium, neither attracting nor repelling each other.

49. In all inquiries into the effects of heat, it is necessary to attend to the following rules respecting the application of the term *Temperature:*—

First. If a body subject to no pressure, or to a constant pressure, have at two different times the same bulk, it is said on both occasions to have the same temperature.

Second. Two bodies are said to have the same temperature if, being kept in contact, the temperature of either remains unaltered by the action of the other.

Third. When bodies of different temperatures are in contact, the temperature of the hotter body decreases and that of the colder increases, till they become equal.

Fourth. If the bodies be equal in mass or in weight, and of the same substance, the increase of temperature in one will be equal to its decrease in the other.

Hence it will be seen that differences of temperature are measurable and comparable with each other, quite independently of change of bulk; that is, without using the latter as a *measure* of temperature, but only as a *test* by which change of temperature is detected.

In this way it has been discovered that the *same* increment (not *equal* increments, as from 40° to 50°, and from 50° to 60°) of temperature causes all masses of the same substance to expand in the same ratio to their whole former bulk; but this is by no means the case with different substances, as is obvious by looking at a common thermometer, an instrument for measuring changes in the bulk of a mass of liquid contained

in a glass vessel of such a form, that changes, very small compared with the whole bulk of the liquid, may cause its surface to rise and fall through a considerable space. Now, this could not be done if the glass and the measuring scale, in undergoing the same changes of temperature as the liquid, experienced also the same change of bulk; for, if such were the case, the liquid surface would always remain opposite the same degree on the scale. The value of this simple instrument, therefore, depends on the fact—that liquids are more expansible than solids.

But it will further be seen that the ratio of the *change* of bulk to the *whole* bulk is different for every different substance, when the change of temperature is the same in all. It is necessary, however, to guard against a very common error respecting the relation between *temperatures* and the *numbers* by which they are represented; namely, the degrees of the thermometer.

Although the *differences* of temperatures are known and comparable quantities, yet their *ratios* are not so. We can compare them by addition and subtraction, but not by multiplication or division. We cannot say, "*This* temperature is so many times *that*," because we do not know the real zero of temperature; that is, we do not know what is the smallest bulk into which a given body is capable of being condensed by cold. We cannot, therefore, say, "*This* body exceeds its minimum bulk by twice as much as *that* body exceeds its minimum bulk;" or, in other words, "*This* body is twice as hot as *that;*" for although the temperature of one body may be 80° and that of another 40°, these numbers are only reckoned from an arbitrary zero or starting point, adopted because the real zero is unknown. But although we cannot say that A has twice the temperature of B, we can say that the tempera-

ture of A exceeds that of B by twice as much as the temperature of C exceeds that of D.

The first question, then, regarding the relation of expansion to temperature, is—"Do equal differences of temperature cause the bulk of a body to vary by equal differences?" This question had to be settled before it could be known whether the common thermometer (the scale of which is divided into *equal* parts) measured differences of temperature correctly. For this purpose, Dr. Brooke Taylor heated two equal weights of water, one to 200° and the other to 100°, and, on mingling them together, he found them to indicate exactly 150°; thereby showing that equal differences of temperature cause equal differences in the expansion of mercury; or rather in the excess of its expansion over that of glass, which is clearly all that the thermometer can measure. More accurate experiments, however, have shown that this rule does not *exactly* apply to any solid or liquid, but only to *gases*. When equal masses of the same liquid, at different temperatures, are mixed, their combined bulk becomes a very little diminished. Liquids, therefore, instead of expanding by equal increments of space for equal increments of temperature, expand *faster* as the temperature increases *equably*; and it appears that the correctness of the mercurial thermometer observed by Dr. Brooke Taylor was the result of a fortunate coincidence, by which the expansion of the glass, which is very small compared with that of the mercury, exactly compensated the increasing rate of the latter. This, however, would not be the case with thermometers constructed with other liquids, for their rates of expansion increase more rapidly than that of mercury. Hence spirit thermometers cannot be depended on for temperatures above the atmospheric range (or above 100°).

The rate of expansion in solids is also found to increase as they become hotter; but it is more equable than that of liquids. Instruments for measuring the expansion of solids are called *pyrometers* to distinguish them from thermometers, which measure that of liquids and airs. The measurement of solid expansion is, however, by far the more delicate and difficult, not only from its smaller amount, but because we cannot measure at once the whole cubical increase or *expansion*, but only the increase of one linear dimension, that is, the *elongation* or *dilatation*. As solids do not in general alter their form by change of temperature, all the dimensions increase and decrease in the same ratio. The only known exceptions to this are afforded by *crystals*.

50. The first effect of heat on solids is expansion. If, however, the heat be more energetic, the solid is resolved into a liquid. The liquefaction of some solids is gradual; they pass through various degrees of softness; but in many, perhaps in most cases, there is no intermediate state between perfect solidity and perfect fluidity: the solid is heated up to a certain point, at which it remains solid; but a very slight increase of heat is then sufficient to liquefy a portion of it. Now, it is an important fact that the same substance always passes from the solid into the liquid state at precisely the same temperature, and this is called its *melting point* if it be above, or *freezing point* if below the medium atmospheric temperature. Thus the melting point of ice, or the freezing point of water, is 32° on the scale of Fahrenheit used in this country; but it is made the zero or 0° degree of the continental scales. The freezing point of mercury is about 70° Fahrenheit lower than 32°, and is therefore called — 38° (minus 38°,) or 38° below zero, a degree of cold which in England can only be produced artificially. By the

same means almost every other body that is liquid at common temperatures has been rendered solid. On the other hand there are very few solids which have not been melted by artificial heat, or by that of the sun concentrated; and each one has its fixed and unalterable melting point. Thus, tin melts at 442°, lead at 594°, zinc at 773°, antimony at 812°, and so on.

But there are important circumstances to be noticed in the liquefaction of these bodies. It is evident that if a quantity of ice, at the temperature of zero, or 0°, be taken into a room whose temperature is 60°, the ice will begin to melt; and a thermometer placed in it, which at first indicated zero, will rise and soon reach 32°; but at this point it will remain *stationary* until the ice has entirely passed into the liquid form. Even if the vessel containing the ice be placed upon a fire, the mercury in the thermometer will not rise above 32° so long as any ice remains in the vessel. Now, it is obvious that, during this time, a quantity of heat must be constantly entering the vessel without rendering its contents hotter; for so long as this influx of heat is engaged in liquefying the ice, it produces no effect upon its temperature. Thus we see that increase of temperature is only one of the modes in which heat or caloric acts, and that when a portion of heat is producing the effect of *fluidity*, it cannot be at the same time producing the effect of *temperature*. The effect here described for ice applies equally to other solids. Hence we see that, during the process of liquefaction, a large quantity of heat *disappears*, or is *absorbed*, so as to be no longer sensible to the touch or to the thermometer. The heat thus lost is sometimes called the *heat of fluidity*, or *latent heat*, in contradistinction to the heat of temperature *.

* It must be remembered, however, that the general principles applied

51. Another general effect of heat is the conversion of liquids, by an enormous expansion, into airs, gases, or vapours, as when water by boiling becomes steam. This effect is attended by the same important circumstance as in liquefaction, namely, the absorption or apparent loss of a large quantity of heat, which, however, reappears when the vapour is condensed again into the liquid form. A vessel of boiling water exposed to the atmospheric pressure of thirty inches maintains the constant temperature of 212°, and the most violent heat is insufficient to raise it above this point. The heat thus expended in vaporizing water without raising its temperature is sufficient to raise it no less than 970° if it were not vaporized; or in other words, the latent heat of steam is nearly 1000°.

52. The axiom laid down in (49) is true only of masses of the *same substance* or *kind* of matter; for different bodies manifest different capacities for heat; that is, if two equal masses or weights, of the same temperature, receive the same amount of heat, they will not become equally hot, even although they do not change their

to mechanical force (33) are equally applicable to force of every kind; it is not lost without producing an equivalent effect. Thus exactly as much of the cause of heat as appears to be lost or *absorbed* in the liquefaction of a solid, is again apparently produced or *evolved* in the resolidification of the same liquid. Thus, as a solid, while melting, becomes no hotter though constantly receiving heat, so a liquid, while congealing, becomes no colder though constantly losing heat; for its temperature is maintained by the evolution of this heat of fluidity. The heat of fluidity in water is about 140°; that is to say, water at 32°, to be converted into ice at 32°, or to be frozen *without change of temperature,* must lose as much heat as would lower its temperature 140° *without freezing* it; for though this cannot be done, yet it can be lowered 10° without freezing, and this by the abstraction of only $\frac{1}{14}$ of the heat which must be removed in order to freeze it; or it can be lowered 20° by the abstraction of $\frac{1}{7}$ of that quantity; or the heat given out in freezing can be made to warm 14 times as much water 10°, or 140 times as much water 1°; and the same thing can be proved in innumerable other ways.

state. For example, if a pound of mercury at 160° be mingled with a pound of water at 40°, the resulting temperature will not be the arithmetical mean, or $\frac{160 + 40}{2} = 100°$; it will be only 45°; so that the 115° lost by the mercury heats the water only 5°. On reversing the experiment, and mingling a pound of water at 160° with a pound of mercury at 40°, the result will indicate 155°; so that the 5° lost by the water raises the mercury 115°*.

Different bodies, therefore, have various degrees of susceptibility to heat. To produce a certain change of temperature requires a greater supply of heat in some bodies than in others. Numbers proportional to the quantities of heat necessary to produce the same change of temperature in equal *weights* of different bodies are called the *specific heats* of these bodies, or their capacities for heat. Thus, water is said to have thirty times more *capacity for heat* than mercury.

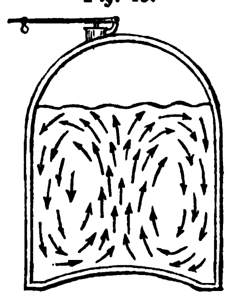
53. There are three methods by which heat is diffused, namely, by *conduction*, by *convection*, and by *radiation*.

Bodies that are kept in contact will (if of different temperatures) gradually change till they acquire the same temperature; that is, their shares of heat of temperature will become proportional to their capacities, and each body will have the same temperature throughout its mass. But this diffusion does not take place instantaneously, or there would be no such thing as difference of temperature. The rapidity with which heat

* Hence it appears that the force of heat, unlike mechanical force, is not proportional to the quantity (or inertia) of the matter affected by it. It is far more nearly related to the *bulk*, though not proportional even to this, when different substances are compared. Thus, if we mix a pint of mercury at 100° with a pint of water at 40°, the resulting temperature will be 60°, or, on reversing the experiment, 80°; showing that 20°, lost by the water, raise the same bulk of mercury 40°, and *vice versâ*.

travels varies in different substances. For example, if we place a silver spoon and a wooden one in boiling water, the handle of the former will become too hot to be held before that of the wooden one is sensibly warmed. We see, then, that silver is a good conductor, and wood a bad conductor of heat. Different substances conduct heat at different rates. If we call the conducting power of gold 1000, silver will be 973, copper 898, platinum 381, iron 374, tin 303, lead 179, marble 23, porcelain 12, clay 11. On placing one hand upon a piece of fur or flannel, and the other upon a piece of metal, both of the same temperature, as they must be if left under the same circumstances, and both colder than the hand, we call one warm and the other cold. This is an effect of sensation merely. The metal being a good conductor, abstracts heat from the hand and gives the sensation of cold; the flannel or fur, being a bad conductor, not only takes away no heat, but allows it to accumulate, and hence the sensation of warmth. Precisely the contrary effect will take place if both bodies are warmer than the hand. The metal will feel hottest, and will even burn us, at a temperature at which the cloth would hardly seem warmer than in the former case.

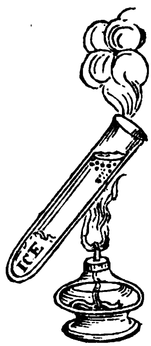
Fig. 19.



54. But in liquids there can be no change of temperature without a displacement of particles. If heat be applied to a vessel of water, the particles near the bottom of the vessel being heated first and expanding, become specifically lighter and ascend; colder particles occupy their place and ascend in their turn, and thus a current is established, the heated

particles rising up through the centre, and colder particles descending at the sides, as shown by the direction of the arrows in Fig. 19. This is evidently a very different process from conduction. The heat is not conducted from particle to particle without displacement, as in the case of a solid; but each particle, as fast as it receives a fresh accession of heat, starts off with it, *conveys* it to a distance, displacing other and colder particles in its progress. This process has received the appropriate name of *convection*, and its importance will be seen if we apply heat to the surface of a liquid instead of to its base. Water being a bad conductor, we may boil it at the surface (Fig. 20), while a lump of ice sunk to the bottom will remain unmelted.

Fig. 20.



Gaseous bodies, however, from the great mobility of their particles, are the most rapid conveyers, although (and, indeed, *because*) they are the slowest conductors of heat. Any body hotter than the air sets in motion an upward current of that fluid, which may be easily seen rising from bodies that are much heated, and the particles which rise are immediately replaced by the influx of other particles from every side. The slightest difference of temperature is sufficient to produce these effects, and hence the rapidity with which the air reduces all bodies to its own temperature. A body colder than the air, such as a lump of melting ice, produces an opposite action: it cools the air in contact with it, which, becoming denser, descends in a continual stream supplied by an influx of air from all sides to the ice, until the whole is melted.

Actions of the same kind in the great scale of nature

give rise to all the varieties of *wind*, by which the whole mass of the atmosphere is kept in motion, and its temperature so far equalized as to mitigate the extremes of climate, and render both the equator and the polar regions habitable. Such effects as these could not take place if the great ocean of air were heated (as at first sight it may appear to be) from above. The atmosphere receives scarcely any of its warmth directly from the sun's rays, but is heated almost entirely by the ground on which it rests, and is therefore in the condition of the water in a boiler, where the heat is applied from below.

But it is different with the liquid masses of our globe. The heat is applied to them at their surface, and is therefore not diffused by convection. It creeps slowly downwards by conduction, so that the temperature of all deep waters is found to diminish downwards. In the absence of the sun, however, the process of *cooling* goes on by convection; the surface waters being cooled first, become denser, and therefore sink, while new portions are brought to the surface, where they are cooled and sink in their turn; by which circulation the whole would very soon be reduced to the freezing point, were it not that the wisdom of the Creator has ordained that the general law of rarefaction by heat and condensation by cold shall, between certain limiting temperatures, be reversed. The operation of this exceptional law has already been mentioned (13). It gives rise (in water below 39½°) to a species of convection exactly the reverse of that in other fluids, namely, a convection of heat more readily *downwards* than upwards.

55. The third method by which heat is diffused is by *radiation*, as when we stand at a distance from the fire and experience its warmth. The heat is not, in this

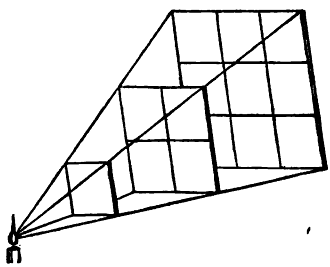
case, brought to us by any current of air, for that must set in *towards*, and not *from*, the fire; and besides, heated currents tend constantly to ascend. Nor can it depend on the conducting power of the air, for that is very slow indeed, and we experience the heat of a fire instantaneously. From these and various other reasons it is evident that a substantial medium path or passage is not necessary for the propagation of heat.

If a red-hot cannon ball be suspended in the air, *rays* of heat will be emitted from it as a centre, in radial lines, which move with the velocity of light, and, like the luminous rays, may be reflected, absorbed, refracted, transmitted, &c., by encountering certain surfaces; and these rays may be reflected or transmitted without disturbing the temperature of the reflecting or transmitting bodies; but if the calorific rays be *absorbed*, (that is, if they are stopped, and wholly or partly cease to exist as *rays*,) an immediate increase in the temperature of the absorbing body is the result. This transmission must not be confounded with conduction of heat. The latter is always a slow process, while the transmission of radiant heat, or calorific rays, is instantaneous. It is the peculiar property of these rays that they do not heat bodies through which they pass, as conducted heat must do. The worst conductors of heat (air and gases) are the best transmitters of these rays, while the best conductors (metals) totally stop the progress of the rays.

The intensity of radiant heat diminishes in the ratio that the squares of the distances from the radiating points increase; that is to say, the heating effect of any hot body (such as the red-hot ball above noticed) is nine times less at *three* feet than at one; sixteen times less at four feet; and twenty-five times less at five feet. Now, as this law applies to all influences that spread

from a centre, such as gravitation, light, heat, electrical forces, magnetism, sound, and in fact all *central forces* when not weakened by any resistance or opposing force, it is desirable to impress the law fully on the reader's attention by giving a reason for it. Suppose a board two feet square (Fig. 21) to be held with its centre exactly two yards from a candle, and another board one foot square to be held parallel with the first board and exactly half way between it and the candle, it is evident that this will exactly intercept the whole of the light that would have fallen on the first board, and no more. But its area is only one-fourth of the first board. Hence we see that the same quantity of light which at *one* yard from its source covers *one* square foot, will, at two yards from its source, be spread over *four* square feet, and consequently be four times less intense. So, also, a board *one* foot square will intercept exactly all the light from another board that is *three* feet square, if the latter be three times as far from the candle; so that any portion of the latter board would receive only *one-ninth* as much light as falls on an equal space of the nearest board. Now, all this must plainly apply not only to light, but to any force that proceeds from a centre in straight lines or rays, and consequently to radiant heat.

Fig. 21.



56. All bodies, when raised to an equal temperature, do not radiate equal quantities of heat in equal times. It is, however, remarkable that the rate at which a body

cools is influenced by the state of its surface more than by the nature of the material of which it is composed. A vessel covered with lamp-black and filled with hot water will cool down to the temperature of the surrounding air almost twice as quickly as the same vessel with a bright polished surface. If we call the radiating power of lamp-black 100, that of writing paper will be 98, sealing-wax 95, crown glass 90, plumbago 75, tarnished lead 45, mercury 20, clean lead 19, polished iron 15, gold, silver, copper, and tin, all polished, 12. It has been proved that the same surfaces which radiate most quickly also absorb rays of heat most quickly; and it is remarkable that these two properties are exactly proportional in all bodies, or, in other words, the same numbers which express the relative radiant powers of any list of substances (as above) will also express their relative absorbent powers.

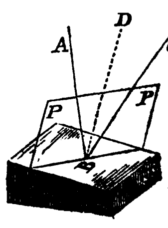
57. By absorption we do not here mean the conversion of sensible into latent heat; but the conversion of radiant into conductible heat. Not all the radiant heat, or rather the radiant effect, which enters a body is immediately *absorbed* or converted into heat: a portion continues its course through the body without warming it; and though more and more is absorbed at every step, yet if the body be not thick enough to absorb all the rays, a portion will emerge on the other side and continue their course till, by the warming of the various media through which they have travelled, all their heating effect has been expended and they cease to exist as rays. The speed with which this is effected is enormously different in different media. Those in which it takes place most slowly are called the most *diathermanous;* but no medium, not even air, is perfectly diathermanous, though a thickness of many miles of it absorbs less radiant heat than a small fraction

of an inch of most solids. Hence the atmosphere is scarcely warmed at all by the sun's rays passing through it, their effect being produced on the ground or sea, which in its turn warms the air, by convection, which we have seen (54) to be necessary to cause *winds*.

58. Not all the radiant effect which falls on the surface of a new medium enters it; a portion is always reflected.

In considering this part of our subject we may remark that *radiations* or effects which are propagated in straight lines only (such as light and radiant heat) are most conveniently considered by dividing them into innumerable straight lines or *rays*, not that there is any such division in nature, but to enable us, amidst the extreme complexity of these phenomena, to confine our attention to the simplest independent portion of the effect. Every individual ray, whether of heat or light, proceeds in a straight line until it meets a reflecting surface, from which it rebounds in another straight line, the direction of which is determined by the law already stated (35), namely, that the angle of incidence is equal to the angle of reflexion, to which, however, in this case must (on account of its generality) be added another condition, viz., that the *plane of reflexion*, as it is called (or that imaginary plane which contains both the incident and the reflected ray), is *perpendicular* to the reflecting surface at the point of contact. Thus let a ray from A (Fig. 22) fall on a reflecting surface at B. We must suppose a perpendicular to this surface erected at the point D, then the same plane P P, which contains both the incident ray and the perpendicular, will also contain the reflected

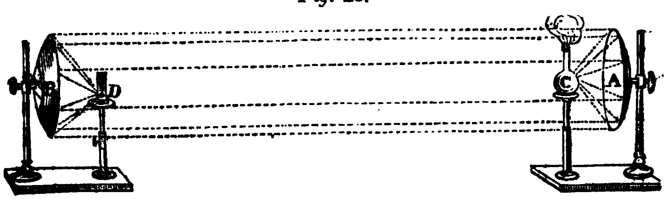
Fig. 22.



ray B C, both rays making equal angles with this perpendicular B D, but on opposite sides of it. When the surface is curved, a perpendicular or *normal* (as it is then called) can equally be erected at any point of it; for it must be remembered that each mathematical point of such surface acts precisely as a tangent plane, that is, as a plane touching the curved surface at that point would act. Thence it happens, that certain regularly curved reflecting surfaces, called *mirrors* or *specula*, possess some remarkable properties. For example, if a mirror have the form of a *paraboloid*, any number of rays radiating from the point called its focus will be reflected into parallel directions, and any number of parallel rays coming to such a mirror are all reflected so as to meet in its focus.

In Fig. 23 two such mirrors, A and B, are shown.

Fig. 23.



They are made of metal and highly polished, because we have seen that this kind of surface is the worst radiator, and therefore absorbs the least proportion of the rays that fall on it, and consequently must reflect the greatest quantity. If these mirrors be truly centered, that is, placed so that their axes may be exactly in the same straight line, and if a hot body be placed at C, in the focus of the mirror A, all the rays which it sends to that mirror will be reflected into parallel lines, and so reaching the other mirror B, will be reflected by it, and all brought to meet in its focus D, where a thermometer

will be affected more than at any other spot, even though such other spot be much nearer the hot body C. Moreover, if a screen be placed either between C and A, or between B and D, the effect on the thermometer instantly ceases.

To render this experiment more striking, a red-hot iron ball is sometimes placed in the focus of one mirror, and some combustible, such as gunpowder, phosphorus, paper, &c., in the focus of the other. These bodies will be burnt, although their distance from the ball C may be ten or fifteen feet.

If, instead of a heated ball, we place in the focus of the mirror A a ball of ice, a thermometer in the focus of the mirror B will be observed to fall. When this experiment was first performed, it was supposed to arise from the *radiation of cold.* This, however, was a mistake; since no principle of cold, considered as a positive quality, can be admitted, cold being merely a sensation arising from the abstraction or diminution of heat; as darkness results from the absence of light, and silence from the absence of sonorous vibrations. In this experiment the thermometer sinks, because it radiates heat to the ball of ice. Hence we learn, that even a body at the ordinary temperature must be constantly radiating heat; and, of course, can only preserve its temperature by the counter-radiation it receives from other bodies. When two bodies are placed in the foci of the opposite mirrors, they are, as it were, isolated or cut off from any other source of heat, so that any heating effect observed in one must be derived from the other. The thermometer, therefore, in the last experiment, has a large proportion of its supply diminished much below its usual intensity, so that (its radiation remaining unaltered) its temperature must sink lower than usual.

59. These generalizations enable us to explain a still more remarkable instance of the apparent focalization of cold. If one of the parabolic mirrors be placed so that its axis* may point to the sun, as the rays coming from a body at so vast a distance are physically parallel, they will all be reflected to the focus of the mirror, so that it will act as a powerful burning mirror. But if the mirror be turned so as to face a portion of clear blue sky, (the bluer and the nearer the zenith the better,) its focus will become a focus of *cold*, and a delicate thermometer placed therein will sink, in clear weather, some degrees even in the day-time, and as much as 17° at night.

Now, in order to understand this effect, it must be remembered that the thermometer is constantly radiating heat in all directions, and also receiving from surrounding bodies, in ordinary circumstances, just as much heat as it radiates. But in this experiment it receives less, because its usual supply from below is cut off by the mirror. But it may be asked, "Will nothing but a mirror serve this purpose?" Any other body would radiate from its own surface as much heat as it intercepts from other bodies; but a polished metallic surface, being the worst of radiators, supplies less heat than it intercepts. It must also have the form of a mirror, the focus of which must coincide with the place of the thermometer, because, if it had any other form, it would reflect to the thermometer some of the rays which it received from other bodies; but, because it is a paraboloid, it cannot reflect to its focus any rays except those that come in a certain direction, namely, parallel with its axis. Now, in that direction no rays come, for there is no body either to reflect or to radiate

* The axis of a paraboloid, or of any mirror, is an imaginary line drawn from its centre through its focus, and prolonged indefinitely.

them. If a cloud, indeed, pass before the axis of the mirror, the thermometer instantly rises to its usual height.

We see, then, by this most instructive experiment, that every substance on the earth, however low its temperature, is constantly radiating its heat in all directions equally; and is also receiving heat in every direction except from the regions of space, or what we call the blue sky. After sunset, the supply of heat from the sun is withdrawn, but radiation still continues; and if there be no clouds to reflect back the heat, the temperature of the earth's surface soon sinks below that of the air which rests upon it, and the consequence is, a condensation of the moisture of the air by the colder earth in the form of *dew*. Any one may convince himself that this condition is necessary to the formation of dew, by placing a thermometer on an open grass plat after sunset, and suspending another thermometer in the air several feet above it. With a clear sky the suspended thermometer will mark a temperature seven, eight, or nine degrees higher than that on the grass.

60. The presence of moisture in the air is accounted for by a modification of the process of vaporization already noticed (51). Water evaporates, or is converted into steam* at all temperatures, until the whole space above it (whether containing air or not) is pervaded with watery vapour of a certain fixed density and elasticity, depending on the temperature, and connected therewith by certain laws. We must remind the reader, that the elasticity or expansive tendency of a fluid is estimated by the number of pounds or ounces with

* By steam we here mean the elastic vapour of water, which is always *invisible*. What is commonly called steam, but properly *cloud*, is liquid water in a finely divided or *powdered* state, wafted like dust by currents of air or of steam properly so called.

which it presses on each square inch of surface that it touches; or by the number of inches of mercury that it will support, as on a barometer.

Now, at any given temperature, steam can exist of such density as to have a certain fixed pressure and no more; and (if there be water enough present) steam will be accumulated till it has this density; but no more can then be accumulated without raising the temperature; and if the temperature be lowered, a portion of the steam will immediately become water, so that (occupying in this state some thousands of times less space than before) it may leave room for the remaining vapour to expand, till its expansive force is reduced to that which the new temperature can support. The pressure of steam is therefore always the same at the same temperature. At 212° its elastic force is equal to that of the atmosphere, and it will support a column of mercury 30 inches high, which is the reason that boiling requires this temperature in the open air, when the barometer is at 30 inches; but rather less or more, when the barometer stands lower or higher*. Above this temperature it becomes *high pressure steam*, which at 220° will support nearly 35 inches of mercury; at 230° nearly 42 inches, and so on. But the steam which is thrown off from the waters of the earth, from damp soil, from the foliage of plants, and even from ice and snow, has but a very small pressure. Steam at 32° will support only 0·200 inches of mercury; at 40°, 0·263 in.; at 50°, 0·375 in.; at 60°, 0·524, or rather more than half an inch of mercury; at 80° it will support one inch, and so on. When the air contains as much vapour as can exist at the existing tem-

* At the town of Potosi, on the Andes, where the superincumbent pressure of air will only support about 18 inches of mercury, water boils at 188°.

perature, it is said to be *saturated*. If in this state it experience the smallest reduction of temperature, some of the vapour must immediately become liquid, assuming the form of cloud, fog, or rain. These effects depend on the cooling of the *air* below the temperature necessary to retain all its vapour. But when a *solid body* is cooled below this temperature, (the air remaining above it,) a different kind of deposition occurs, called *dew*, which does not fall in drops from the air, but *grows*, as it were, on the solid. Dr. Wells proved, by a most complete investigation of this subject, that instead of dew cooling bodies, as commonly supposed, it is their cooling which causes dew; and its formation even mitigates the cold, by the heat previously *latent*, which the steam gives out on condensing into water. The degree of heat at which dew begins to be formed is called the *dew point*, and instruments called *hygrometers* have been invented to measure it. The difference between the temperature of the dew point and the temperature of the atmosphere indicates the degree of dryness, which in this country seldom reaches 30°, that is, the temperature of the earth necessary to condense the vapour of the air is seldom 30° below the temperature of the air. In India it has been known to be 61° below it, and in Africa probably lower still.

If, while dew is forming, the earth continues to cool down until it reaches the freezing point, *hoar frost* is formed. The beautiful figures seen in winter on the inner surface of our window panes, cooled by the external air, are produced by these cold surfaces condensing the moisture of the warmer air within.

As the amount of radiation varies in different bodies, so the depression of temperature varies with the nature of the radiating surface. By a beneficent provision herbage and low plants are good radiators, and thus

receive a much larger amount of dew than rocks, bare earth, and masses of water, which do not require the refreshing influence of dew. Its value is, of course, most appreciated in warm climates; and in several passages of Scripture it is mentioned as one of the choicest blessings. Thus, among the blessings invoked by Isaac upon his son, was "God give thee of the dew of heaven."* And Moses, blessing the land of Joseph, places the dew among "the precious things of heaven."†

61. There are various other phenomena of heat which ought, in a more extended treatise, to be brought under the notice of the reader; indeed we have already exceeded the limits which this portion of our subject ought to have occupied; but as many of the phenomena already noticed for heat belong also to light, we can afford to be more brief in considering that wonderful agent.

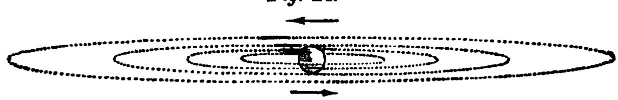
The hypotheses which have been applied to the nature of heat have also been applied to light. In our own day, philosophers incline to the opinion that light is produced by the undulations in, or vibrations of, an elastic ether, while it was formerly supposed to be an emanation of material particles from luminous bodies. Without further reference to either of these hypotheses, we may examine a few of the elementary effects to which a *ray of light* is subject under various circumstances.

62. The simplest induction will prove that some substance or action, which we call *light*, *travels* from every visible point to the eye in straight lines, radiating in all possible directions from every visible point of matter, whether emitting light from its own resources, or dispensing what it receives from some foreign source;

* Gen. xxvii. 28. † Deut. xxxiii. 13.

yet the speed of the transference of light long baffled all attempts of philosophers to measure or even detect the time it occupies in travelling the greatest distances. To make signals on two distant hills, in the manner described for ascertaining the velocity of sound, (43), is in vain, because light appears to occupy absolutely *no time* in reaching from one hill to the other. But there is something so incredible in this, that Lord Bacon, with remarkable penetration, foretold the method by which its progressive motion would be detected, viz. by more careful observation of the heavenly bodies; and the prediction was thus verified:—About the year 1675, Römer, an eminent Danish philosopher, called attention to the important fact, that the eclipses of the four satellites, or moons, which revolve round Jupiter, did not begin or end (that is, these little bodies did not plunge into or emerge from the shadow of Jupiter) pre-

Fig. 24.



cisely at the times assigned by calculations founded on previous observation*; but that, if the data of these calculations were obtained when Jupiter was in opposition, or *nearest the earth*, they would give too early a date for the eclipses at all other periods of the year; and, after many years' observation, he found that this retardation (which might sometimes amount to nearly a quarter of an hour) increased or diminished exactly as Jupiter's *distance from the earth* varied; so that the only conceivable way of accounting for it was by supposing that the last gleam of light shed previously to

* Our figure represents Jupiter and the orbits of his four moons when seen *least edgewise*, or with the orbits opened to the greatest apparent width possible.

a moon's immersion into the shadow of the planet, or the first ray that it reflected on its emersion, did not reach the eye until some time after the emersion or immersion; hence the retardation would, of course, be increased as the distance of Jupiter from the earth increased. Knowing the distances of the principal heavenly bodies from each other, and testing those distances by the apparent retardation of the eclipses of Jupiter's satellites, it has been found, that the light reflected by them must occupy, in reaching us, about 34 minutes when we are nearest them, and 50 minutes when we are furthest off, the rate of travelling being 192,000 miles in a second; consequently it hardly occupies a *second and a quarter* in coming from the moon, a distance equal to 10 times the earth's circumference. But such is the prodigious disproportion between the distances of the celestial bodies, that this same agency must take 8¼ *minutes* in reaching us from the sun; about 5 *hours* in coming from the new planet Neptune; not less than *years* from the nearest fixed star, and probably *centuries* in coming from the nearest nebulæ; so that we see the nebulæ not as they are now, but as they were some centuries ago.

That the light from all these sources travels with the very same speed is known by a singular phenomenon called the *aberration of light*; which fully confirms the conclusions drawn from the above-named observations of Jupiter. This aberration is common to *all* the heavenly bodies, causing them all to appear a little out of their true place, and it forms one of those corrections which must be applied to every celestial observation. It arises from an application of the principle advocated by the sportsman, of "shooting *before* the hare." As the observer is moving along with the earth, at the same time that the light is travelling to him, it follows that,

if he point his telescope exactly towards any celestial object, he will not see it, because the light which enters the telescope will, before it can reach his eye, be struck by the side of the tube, (unless, indeed, he be travelling exactly *towards* or *from* the object, in which case there is no aberration). In other cases, the telescope must evidently be pointed a little to one side of the object in order to see it, so that almost every star is seen out of its place. Now, the amount of this displacement being ascertained, is found in all cases (whatever be the object seen) to be exactly such as may be calculated from the known velocity and direction of the earth's motion, taking the velocity of light always at the same rate, viz., 192,000 miles a second. We should observe that, as the earth's motion is very slow compared with this, (barely a 10,000th so fast,) the amount of the aberration is very small, never exceeding $20\frac{1}{2}''$, or about half the apparent diameter of Jupiter.

63. The motion of light in *straight lines only*, (under ordinary circumstances,) is probably the first physical fact that we learn, and that on which we found every inference depending on the evidence of vision. It is to some exception to this law that every variety of ocular illusion or deception is referable; for when the rays coming from any object suffer any bending before arriving at the eye, it sees the object out of its true direction, viz., in that direction which is *last* assumed by the rays immediately before entering the eye.

Light not only proceeds ordinarily in straight lines, but such lines or rays emanate from every point of a visible object, and proceed in every direction. Any number of rays of light can cross each other in the same point of space without jostling. If a small hole be made from one room into another through a thin screen, any number of candles in one room will shine

through this hole, and illuminate as many spots in the other room as there are candles in this, all their rays crossing in the same hole, without hindrance or diminution of intensity, just as sounds of different character proceed through the air, and speak to the ear, each in its own peculiar language, without materially interfering with each other.

Owing to the rectilinear motion of light, the *pencil* (as it is called) which emanates from any point diminishes according to the law of inverse squares (55), and the apparent superficial size or area of any object diminishes as its distance from us increases by the same law. Hence, as its apparent size and the whole quantity of light received from it are always proportional, its *brightness* remains the same at all distances, and the sun appears no brighter from Mercury than from the earth. This, however, is only true in free space, and not in air, because a portion of the light is *absorbed* in passing through air, as explained in the case of heat (57), causing the intensity to diminish rather *faster* than the inverse square of the distance.

The investigation of these effects, and all others deducible from the law of straight-lined motion alone, constitutes the first branch of optical science, called *Perspective.*

The application of this science, when no account is taken of the absorptive power of the medium through which we see, constitutes *Lineal Perspective;* when this consideration is added, it becomes *Aërial Perspective.*

64. The second science of light, called *Catoptrics,* investigates whatever is deducible from the law of *reflexion,* already explained in the case of heat (58).

As when a moving body strikes another at rest, the mechanical force is divided and shared between them; so when the action of light, propagated through any medium,

arrives at the surface of a new medium either denser or rarer, more or less transparent than the former, its force is divided, a portion entering the new medium, and a portion rebounding into the old. This latter portion belongs to Catoptrics. Its quantity rarely exceeds *half* the original light, except in one case, to be noticed presently, where it includes the *whole* effect. When the portion reflected from any surface, or point of a surface, to the eye is considerable, such surface or point appears *white;* when very little, it appears *dark coloured;* and *black* when the portion is inappreciable. In like manner, the textures of different surfaces is judged of by the quantity of light which they reflect, and the mode of reflecting it.

Our space will not allow us to enter further into the subject of Catoptrics, but we may observe, that all the appearances of opaque bodies, (apart from colour,) and all the images of other bodies appearing either behind or before mirrors or reflective surfaces, whether such images be true or distorted representations, erect or inverted, magnified or diminished, may all be accounted for by the law of equal angles, as those of perspective are from that of straight-lined motion. In fact, Catoptrics is a science of which the inductive part has long been completed, and its further progress belongs to deduction.

65. We have seen that, in general, only a portion of the light which meets any surface is reflected, the remainder being absorbed or transmitted. When it is absorbed, the substance is said to be *opaque;* but when we can trace it further, the substance is called *transparent.* When light passes from one medium into another (unless its direction be perpendicular to the surface dividing them,) that direction undergoes a sudden change which is called *refraction.* The investiga-

tion of this property belongs to the third branch of optics, called *Dioptrics*. The new direction assumed by the ray is regulated by the following laws. Let A A, Fig. 25, represent the surface of calm water, which is necessarily polished, as that of all fluids must be, by the operation of the molecular forces. No light will pass through this surface unrefracted, unless it either descend or ascend perpendicularly, as from P to P,′or P′ to P. Any ray which falls obliquely, as B C, will be suddenly bent into the direction C B″; and if it arrive more obliquely, as D C, it will be *more* bent, taking the direction C D″. It will be seen that in both cases the tendency of refraction is to render the ray more nearly perpendicular to the surface than before. But any ray which proceeds from the water into the air undergoes a contrary effect, being rendered *less* perpendicular to the surface. Thus, a ray ascending in the direction B″C will, on emerging, take the direction C B; and one which, in the water, travelled along D″C, will, in the air, be bent into C D; the bending in this case, no less than the former, being greater the more oblique the ray may be to the surface. Moreover, it is a law in refraction no less than in reflexion, that by whatever path a ray reaches one point from another, by the very same path will a ray travel from the second point to the first.

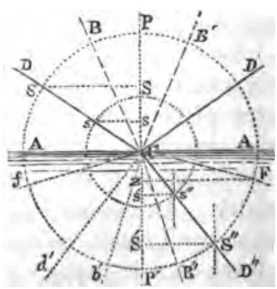
An eye at D″, then, will see the object D, not in the direction D″ D, but in the direction D″ C, higher than its true place; and an eye at D will see the object D″ in the direction D C, also higher than its true place, of which any one may convince himself with a basin of water. An opaque body placed at C will hide D and D″ from each other, though not in a straight line between them; and if it were in the straight line, it would not hide them, for they see each other round a corner at C.

The *law* of refraction was first completely established

by Snell and Descartes at the commencement of the seventeenth century. The first part of this law is similar to that of reflexion, viz., that the angles of incidence and refraction (*i.e.* the angles which the incident and refracted ray each make with the perpendicular or normal of the surface, or in this case the angles P C D and P′ C D″,) are both *in the same plane.* Any ray meeting the surface of a new medium is split into two rays, one reflected and the other refracted; as, for instance, the ray B C into the reflected ray C B′, and the refracted ray C B″; or D C into the two rays C D′ and C D″. So, also, a ray B″ C will be partly reflected in the direction C *b*′, and partly refracted into C B; or D″ C will be reflected into C *d*′, and refracted into C D. Now, in all these cases, the three rays, incident, reflected, and refracted, will be all in one plane, and that plane perpendicular to the acting surface A A.

The angles of incidence and reflexion (such as P C D and P C D′) are, as already explained, invariably equal; but that of refraction (in this case P′ C D″) is different from both, but connected with them by this law, that (at the same surface) the *sines** of incidence and refraction, to the same radius, bear a constant ratio to each other, which is always the same in the same two *media.*

Fig. 25.



For instance, in passing through the surface A A, at whatever degree of obliquity, and whether upwards from the water into the air, or down from the air into the water, a ray is invariably so bent that the angle it makes with the

* The *sine* of an angle is any line dropped from a point in one of its

perpendicular PP′ *in the air* may be greater than that *in the water;* and that the *sine* of the angle in air may be to that in water (to the same radius) as 4 to 3, which is the ratio that has been determined by experiment. At the surface separating any other two media, a different ratio would be observed with equal constancy.

If we want to find the new direction into which any ray, such as DC, will be bent by this surface, we draw a circle round the point C with *any radius*, such as CS, and we find the sine of the ray *in air* (to this radius) to be SS. Therefore the sine *in water* will be $\frac{3}{4}$ of SS. Draw a line parallel with CP′ at a distance therefrom equal to $\frac{3}{4}$ of SS, viz. at the distance S′S″, and as this intersects the circle at S″, we know that the refracted ray must pass through S″ to make its sine in water (S′S″) $\frac{3}{4}$ of its sine in air (SS) both to the same radius (CS or CS″). If any other radius had been chosen, as C*s*, it is plain that we should have obtained the same result; for, by the property of similar triangles (21), if S′S″ be $\frac{3}{4}$ of SS, then *s′s″* is also $\frac{3}{4}$ of *ss*.

66. If we were tracing the course of a ray upwards from the water, as D″C, then, having found its sine *in water* to any fixed radius, we should make its sine *in air* $\frac{1}{3}$ greater, because the sine in air is always greater than that in water, as 4 : 3; and we should thus find the new direction of the ray to be CD.

In this case a very singular effect would take place

legs perpendicularly to the other leg, and may therefore have any length. Thus, the sine of PCD (Fig. 25,) may be either SS or *ss*, or any other line parallel with them, intercepted by the two legs of the angle PC and CD. The sine *to a given radius* is found by drawing a circle with that radius round the angular point, and from wherever this circle crosses one leg dropping a perpendicular to the other. It can therefore only have one length, and (in the same angle) will always bear the same proportion to the radius, however long or short that may be. Thus the sine of the angle PCD to the radius CS is SS, but its sine to the radius C*s* is *ss*.

if the ray were very oblique to the surface, as FC. We should first remark that *no* ray passing from the air into the water, however obliquely, could ever be refracted into the direction CF; for this reason—The sine of no angle can be greater than the radius to which it is drawn; therefore no ray can have its sine to radius CS greater than CS. But its sine in water is only $\frac{3}{4}$ of that in air, and consequently cannot exceed $\frac{3}{4}$ of the radius. Now, the sine of the ray CF, viz. F*z*, is more than $\frac{3}{4}$ of the radius CS; therefore no degree of obliquity of the ray in air will enable it to become so oblique in the water as CF. But a ray may ascend in the direction FC as well as in any other. Now, its sine in air must become $\frac{1}{3}$ greater than F*z*; but this is impossible, for a line $\frac{1}{3}$ longer than F*z* would be longer than the radius CS, and therefore too long to be the sine of any angle to that radius. As this ray, then, cannot be refracted *according to the law*, it is not refracted *at all*, but *totally reflected* in the direction C*f*, the only known instance of total reflexion, for none of the light can penetrate the surface AA, which is, in fact, absolutely *opaque* to this light. This phenomenon of *total reflexion* may be seen by looking through the side of a tumbler containing water up to its surface, in some such direction as *f*C, when the surface will be seen to be opaque, and more reflective than any mirror, inasmuch as the images in it are perfectly *equal* in brightness to the objects themselves.

67. We have said that, at the surface between any other two media, the ratio of the sines would be different; for though all surfaces *reflect* alike, (as regards the direction of the ray,) all do not *refract* alike. Suppose the ray passed from *vacuum* into *water*, the ratio would be rather greater than 3 : 4, namely 1 : 1·335. In passing from vacuum into air of the common density, the

refraction would be much less, and consequently the sines much more nearly equal, viz., as 1 : 1·000294. Now, if the sine in any medium be called 1, the corresponding sine *in vacuo* is called the *index of refraction* of that medium; and is *specific* for each substance, or as constant as its density, expansibility, specific heat, or any other measurable quality. Thus the refractive index of *air* of the common density is 1·000294, that of water 1·335, of crown glass 1·52, of flint glass 1·55.

Now, in the case above considered of refraction from air into water, and *vice versâ*, the sines in air and in water are, strictly speaking, as 1·335 : 1·000294; and generally the sines on each side of any surface are *inversely* as the refractive indices of the two media.

The refractive indices of a great many media have been measured and arranged in tables. When the density of any substance is increased or diminished, its refractive power is increased or diminished in the same ratio.

68. The application of the laws of refraction accounts for numerous deceptive effects seen in the atmosphere, and included under the general term *mirage;* the most familiar of which is the distortion of objects seen through a rising current of hot air, which, from its smaller density, has a lower refractive power than the surrounding cold air, and therefore bends the rays in various directions. It is also plain that the rays of the heavenly bodies coming from space into our atmosphere must be refracted, and thus cause the objects whence they come to appear rather *above* their true place, as the eye at *d*, in Fig. 25, sees D in the direction *d* C rather above its true place. This forms one of the sources of error to be allowed for in all astronomical observations, and tables are calculated for finding its amount, depending on the object's apparent alti-

tude, and the state of the barometer and thermometer. Owing to the very small refractive power of air, however, this error is hardly sensible when the object is high, but increases rapidly towards the horizon where it becomes 33′, or rather more than the sun's or moon's diameter, so that these bodies may appear just clear of the horizon when they are really completely below it. As the density of the air diminishes *gradually* upwards, atmospheric refraction is not, like that which we have just considered, a *sudden* change of direction, but the ray actually describes a *curve*, being refracted more and more at every step; and this applies equally to the light from a distant terrestrial object which is either lower or higher than the eye, because it must pass through air of constantly increasing or diminishing density. This refraction has therefore to be allowed for in *levelling*, which is done by assuming that the light from a distant object comes to us in a line arched or curved upwards, the radius of which is about seven times that of the earth.

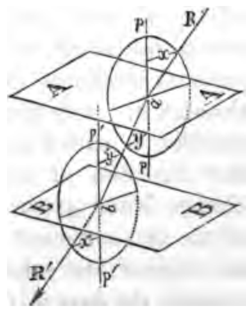
The application of these laws of Dioptrics has also led to the understanding of the mechanism of the *eye*, and hence to the imitation thereof by *lenses*, affording the remedies for its infirmities of *long* and *short sight*, and disclosing the wonders of the *telescope* and the *microscope*.

69. In order to understand the action of lenses, we must remember that, as a lens has necessarily *two* refracting surfaces, the direction taken by a ray after passing through it must depend mainly on the relative inclinations of the two surfaces to *each other* at the points where it crossed them. Sometimes one surface partly or wholly undoes the effect of the other, and sometimes adds to that effect.

Let us first examine, then, the progress of light

through a piece of plane or parallel glass, of equal thickness throughout. Let A A and B B (Fig. 26) represent portions of the two surfaces of such glass, and let a ray from R fall obliquely on the surface A A at *a*. To find the new direction it will take, we must first draw *p p* through the point *a*, perpendicular to the refracting surface A A. Now, by the first law of refraction, we know that the refracted ray will be in the same plane which contains the incident ray R *a*, and the perpendicular *p p*. In this plane, therefore, and with any radius, we draw a circle round the point *a*, and we find the sine of incidence to be *x*. Now, by referring to the tables, we find the index of the refraction of *glass* to vary from 1·521 to 1·58, according to the *kind* of glass. But, for simplicity sake, we may suppose it to be generally about $1\frac{1}{2}$ times that of *air*. Therefore the sines in air and in glass (to the same radius) will be as 3 : 2 ; and by making the sine in glass (viz. *y*) equal $\frac{2}{3}$ of *x*, we find the new direction of the ray to be *a b*, meeting the second surface B B at *b*. Here we erect a new perpendicular *p′ p′*, and draw a new circle which is obviously in the same plane with the former circle round *a*, and (supposing both circles to be equal) it is plain that the sine *y′* in the second circle is equal to *y* in the first. Now, the new sine in air (viz. *x′*) must be $1\frac{1}{2}$ times the length of *y′* or *y*, and therefore will just equal the original sine *x*. Hence we see that the emergent ray *b* R′ will have the same direction as the original incident ray R *a*, though not in the same line with it. Thus we see that a ray

Fig. 26.



can suffer no permanent change of *direction* by passing through a parallel-sided plate of any medium, although it suffers a small lateral displacement depending on the *thickness* of the plate, which displacement may be easily seen in viewing this page through a piece of *thick* glass.

70. This property of parallel-sided glasses, by which their second surface exactly undoes the refractive effect of the first, renders them so well adapted for windows. But by the same reasoning which shows us that two parallel surfaces will compensate each other's effects, we shall also see that, to produce this compensation, the surfaces must be parallel; so that glass of unequal thickness displaces and distorts objects seen through it. Any glass having two *plane* surfaces, not parallel, is called a *prism;* and it permanently alters the direction of every ray passing through it, the change being greater in proportion as the inclination of the two surfaces* is greater. On looking through it, all objects are seen removed from their true place towards the *base* or *thicker part* of the prism, whether that be turned upwards, downwards, or to either side.

71. But however much a prism may change the general direction of each *pencil*† of light that passes through it, it can effect no change in the relations of the various rays which compose each pencil. These

* Technically called the *refracting angle.*

† *Pencils* of light are so called from their property of *painting* on a screen an image or picture of the points whence the pencils originally came. This resemblance is not seen in any one point alone, but when the other pencils, proceeding from all the surrounding points of the object, are each separately concentrated on as many different points of the screen, all these points or *foci* shine with the same quantities and intensities of light, relatively to each other, as did the corresponding points of the object; so that they must form an exact picture thereof, such as is painted on the retina of the eye and in that beautiful toy the *camera obscura,* which is an imitation of the eye.

all proceeding from one point necessarily diverge (55), but the further we recede from their point of origin, the less divergent will any small portion of them be; and when the point is at a vast distance, as in one of the heavenly bodies, all the rays of each pencil may be regarded as *parallel*, although the different pencils have different directions.

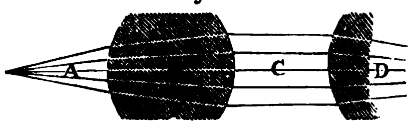
Now, no *plane* surface or combination of plane surfaces can ever increase or diminish the divergence of a pencil passing through them, still less render a divergent pencil parallel, or *vice versâ;* and as in the eye and all other optical instruments it is necessary that this should be done, and even that they be made to *converge* and meet or *focalize* in one point, and again diverge therefrom as from a new source, advantage is taken of the refractive effect of the *curved* surfaces of *convex* and *concave lenses* *. It is obvious that a pencil of parallel rays meeting with a curved surface must all have different inclinations thereto, and consequently all must undergo different amounts of refrac-

* When the various pencils coming from any object are thus separately focalized in different adjoining points of space, these points evidently form a repetition or *image* of the object, suspended in space, and differing from a real object only in this—that each point of a real object radiates a *sphere* of light, so as to be seen in every direction, whether the eye be above, below, or on any side of it, while each point of an optical image radiates only a *cone* of light so as to be seen only by an eye placed in that cone.

This image may be either larger or smaller than the object, and may be brought as near to us as we please, so that we may examine details in it which are invisible in the real object on account of its distance. Such an image is formed in every telescope and in every *compound* microscope. In the latter it is *larger* than the object; in the former incomparably *smaller*; but in both it is brought very near the eye, too near to be seen without the intervention of an eye-glass, the action of which is (by combining with that of the lenses of the eye itself) to render it for the time unnaturally *short-sighted*. For by adding other lenses to its own, the eye can be made to see at the distance of an inch, or even one-tenth of an inch, as in using a *simple* microscope.

tion, so that they can be no longer parallel after passing through the surface. Now, whether they be entering or emerging from the surface, that is, whether they pass from a rarer medium into a denser*, or *vice versâ,* in either case they will be rendered *divergent* if the surface of the denser medium be concave, and *convergent* if it be convex. Let us further inquire into the opposite effects produced by these surfaces upon a *single* pencil of light, the rays of which are not parallel, but either *divergent*, or already rendered *convergent* by the action of some other surface.

Fig. 27.



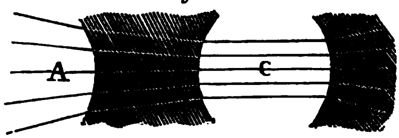
First. By convex surfaces every pencil already convergent is rendered still more so. Thus the rays B (Fig. 27) proceeding through a convex surface to A are made to converge more quickly than before, so as to focalize sooner than they would otherwise have done. With regard to divergent rays, they are at least rendered *less* divergent by passing through this kind of surface. Thus the rays at A passing to B have their divergence diminished. But in certain cases, viz., when their original divergence is not too great, it may be altogether destroyed, and they may be rendered parallel, as the rays B proceeding to C; and if their divergence had been still less, or the surface more convex, or the medium more refractive, they might at once be changed from a divergent into a convergent pencil, as the rays from B passing through *two* convex surfaces

* *Optical* density or refractive power is here meant, which is not proportional to mechanical density in different substances. For example, oil is mechanically rarer but optically denser than water.

to D, become convergent, an effect which might have been produced by a single surface if it had been sufficiently powerful.

Secondly. By concave surfaces, on the contrary, a divergent pencil is made to spread still faster, as in going from B to A, Fig. 28. And a convergent pencil

Fig. 28.



has either its convergence diminished, as from A to B (thereby delaying its focalization, though not preventing it), or its focalization is prevented by rendering it a parallel pencil, as in passing from B to C; or, if the surface be strong enough, the pencil is changed from convergent into divergent, as by the joint action of the two surfaces B and D.

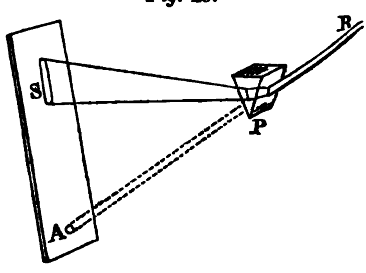
72. The *focal length* of a convex surface or lens is the distance at which it will focalize a pencil of rays previously parallel, or at which it will therefore form on a screen a distinct picture of any very distant object, such as the sun (p. 119, Note). This is also the distance at which it must be placed from the source of any divergent pencil to render it parallel. But the focal length of a concave lens is equal to that of a convex lens, such as will just neutralize it and produce the effect of a plane glass: or, it is the distance at which a pencil which it renders parallel (or just prevents from focalizing) would have focalized if not intercepted by it.

73. Although refraction is a property common to light of all kinds, yet this property is not possessed *equally* by different kinds of light. As sounds differ in many

respects besides loudness, and as radiant heat (apart from any difference of intensity) differs in the qualities of refrangibility and absorbability by different media, (56), so also do rays of light differ in the degrees of these same qualities, independently of their difference of brightness; and these differences, in so far as they are distinguishable by the eye, constitute *colour*. Differences of quality, not distinguishable by the eye, constitute *polarization* (85).

The law of refraction, that the sines of incidence and refraction always bear the same ratio at the same surface, is true only as regards rays *of the same colour*, or coming from objects of the same colour. Moreover, light, which we call *colourless* (as that coming immediately from the sun), really contains light of all possible colours so mixed as to neutralize each other. This capital discovery was made by Sir Isaac Newton in the following manner:—Having closed the windows of his apartment, he made a small hole in the window-shutter, so as to admit a sun-beam R (Fig. 29), which, proceeding in a straight line, illuminated a spot on a screen placed to receive it at A. Now, by means of a prism, which we have seen (70) effects a permanent change in the direction of the light that passes through it, we can turn aside this sunbeam in every direction. Thus, if the base of the prism be downwards, the beam will be turned downwards; but a prism turned base upwards, as at P, will refract the beam upwards, so that it will no longer illuminate the

Fig. 29.



spot A, but some spot much higher, as S. Now, it is very remarkable that this spot S, instead of being similar to A in shape, is greatly *elongated* (its breadth remaining unaltered); and, whereas A was colourless, the lengthened spot S exhibits a continued gradation of the most intense colours, the lower end being *red*, which passes upwards into *orange*, this into *yellow*, then *green*, *blue*, *indigo*, and *violet*, which is at the upper end. The very same colours will be seen, and in the same order, whatever way the prism may be turned; for, whether the spot S (called the prismatic *spectrum*) be above, below, or on either side of A, its red end will always be *nearest*, and its violet end *farthest*, from A.

Hence we see that the various rays composing the parallel pencil R do not remain parallel after refraction, even by two *plane* surfaces (contrary to what has been advanced) (69), and consequently these rays must have suffered *different* amounts of bending, though falling on the prism under precisely similar circumstances; and this will be found to be true also in every other case of refraction, whether produced by a prism or a single surface, and whether by glass or any other solid or liquid medium. The same rays that are most bent by passing from air into glass are also most bent in passing from glass into air, or into water, or any other medium, and are therefore said to be the most *refrangible*.

Moreover, it appears that the rays which are *least* bent are always *red*, those *most* bent always *violet*, and the others of intermediate colours, though before separation they were colourless. It became an interesting question, then, whether, if reunited, they would again compose colourless light, and this Newton proved by many convincing experiments, the most complete of which perhaps consisted in receiving the divergent beam

at s, on a convex lens, when the focus at which all the coloured rays met was found to be perfectly colourless.

74. If, however, in this last experiment, the lens be not wide enough to include the *whole* of the coloured beam, or if a portion thereof be purposely intercepted, the focus of the remainder will not be white, but tinged with some colour, which will be pale if only a *small portion* of the spectrum be thus intercepted, but more decided the more of the spectrum be omitted from its composition; and there is no colour, tint, or shade, in the whole circle of nature or art, which may not be thus *exactly* reproduced by a mixture of part only of the components of white light.

This important fact may be further shown thus. If we look through a prism at some small *white* object or spot on a *black* ground, it will be seen not only out of its place, but lengthened, and coloured with the entire series of prismatic colours, forming a complete spectrum, of which the red end is nearest the true place of the spot (as seen without the prism). The same will occur if the spot be *grey* or of a neutral tint, showing that, though it reflects less light than the white object under the same circumstances, yet it reflects the same kind of light, or a mixture of the same colours. In fact, a good neutral tint should differ in no respect from a white *less illuminated*, so that, by regulating the intensities of light which they receive, they may be made to appear exactly alike. But, if the object examined through the prism be *coloured*, it will not be lengthened so much as the white or grey object; for some portion of the spectrum (either one end, or both, or the middle) will be *missing*, and the portion which appears will show what portion of the complete (or solar) spectrum must be focalized (apart from the rest) to imitate the colour of this object.

Fig. 30.

Now, if the object here used be of a very pure and intense colour (such as vermilion or ultramarine), it will scarcely appear elongated or at all changed in appearance, showing that all the rays coming from it are nearly of the same kind and equally refrangible. But Newton showed the different refrangibilities of these two colours by the following very simple and conclusive experiment. A little rectangle of paper, coloured half red and half blue (as B R, Fig. 30), was placed on a black ground and viewed through a prism. When this was so turned as to see the paper above its true place, as at *B R*, the blue half was seen raised higher than the red half, as here shown; and when both were depressed below their true place, as at *b r*, the blue was seen to be depressed the lowest, so that in both cases it was more displaced, *i. e.*, its rays were more refracted than the red.

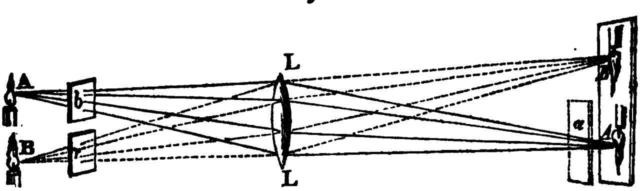
If this experiment be varied by using the two colours finely powdered, and mixing them together so as to appear *purple*, neither the red nor the blue grains being distinguishable by the eye, the prism will nevertheless effect their complete apparent *separation*, so that, if the spot of purple be small, it will appear divided into two distinct spots of *red* and *blue;* but, if it be too large for its two images to be detached, it will only appear *fringed* with red on the upper edge and blue on the lower, or *vice versâ*, the middle part, where they overlap, remaining purple. On this principle, therefore, we may easily explain all the coloured fringes seen to surround objects viewed through a prism, a lens, or any other glass of unequal thickness. All this is due to the *decomposition of light* by refraction, in consequence of its rays having different degrees of refrangibility and different colours.

The ratio between the sines (67), in any two media, being different for rays of different colours, it follows that the index of refraction given in the tables above mentioned (67) for each medium only applies to rays of a particular colour, viz., those of the *mean* refrangibility, or *middle colour* of the spectrum, viz., green. Thus the index of *water* for these rays is 1·335851, but for some of the violet rays it is more than 1·344, and for some of the red less than 1·330; and there exist rays having every possible index of refraction (by water) between these two extremes.

75. A similar difference, though not in the same ratio (generally a greater), exists between the refrangibilities of these rays by every other medium, whence Newton concluded that the focal length of a curved surface (72), or of a lens, must be different for different colours, and that, as the light of most objects contains rays of various refrangibilities, it cannot be truly focalized to one point by any lens, thus accounting for the confusion of colours seen at the edges of the image formed in a telescope, which confusion, and consequent indistinctness, was at that time the greatest obstacle to the progress of astronomical discovery. He tested the truth of this conclusion by the following simple experiment, among many others:—

Let A B (Fig. 31) represent two candles, and L L a convex lens placed at an equal distance from both, viz., about twice its focal length, or rather less. A pencil of rays from the candle A will be brought to

Fig. 31.



a focus at some point A', where a white screen must be placed to receive them, and a pencil from B will likewise be focalized at B' on the same screen. Now, for the same reason that these foci are at different spots, all the innumerable pencils coming from the different points of each flame will be concentrated on different points of the screen, so as to form an exact image of the candle, if the screen be at that precise distance from the lens at which the rays focalize. As the rays from the lower candle, however, go to the upper image, so those from the foot of each flame go to the top of the image, and *vice versâ*, so that both the images are inverted. Now, place before the two candles a blue and a red glass, as *b r*, the images will of course assume the same colours; but it will now be found impossible to place the screen in such a position as to make *both* images distinct. This can only be accomplished by receiving them on separate screens, viz., the blue image on a screen *a*, rather *nearer* the lens than that which receives the red image. They will then be more distinct than they can ever be made without the coloured glasses.

If we point a common (non-achromatic) telescope to a blue and a red handbill at a short distance, we shall have to draw it out to a greater length in order to read the red than the blue bill. But with this precaution both can be read at a greater distance than a white bill. The same difference will be observed in looking at the sun with a blue or a red darkening glass.

For the same reason the focus of a burning-glass (which is in fact an optical image of the sun) is never perfectly distinct, but always confused by a blue or a red border, because the various coloured rays of which sunlight is composed cannot all be focalized at once.

76. As the same cause for imperfect focalization exists

in every refractive medium of which a lens could be formed, Newton concluded that no good telescope could be made on the dioptric principle, and that the only perfect focus would be that formed by *reflexion* from mirrors or specula (as explained in the case of heat) (58); for the law of reflexion (unlike that of refraction) is the same for *all* rays, of whatever colour. He therefore turned his attention to devising a *telescope* that should act by *reflexion*, and soon invented that noble instrument by which (almost without a change, except in size) the latest discoveries of Herschel and Lord Rosse have been made.

But we owe this grand invention to an oversight of Newton; for soon after his death it appeared, from a closer examination of the phenomena of colour by Euler and others, that what Newton had regarded as impossible, viz., refraction without dispersion of colours, was possible; and another Englishman, Dollond, had the merit of first accomplishing this by an application of the same abstract principle which is displayed in the compensation pendulum, and may be thus exemplified. Though we can find no metal which does not expand by heat, so as to be no longer in summer than in winter, yet, because all metals do not expand in the same ratio to their entire length, we can so combine them as to form a pendulum whose length shall never vary; for its length can be made to depend on the *difference* between the lengths of two bars of different metals, which, though of unequal lengths, may yet expand by an equal increment for the same increase of temperature, so that their difference may remain invariable.

In the same manner, though we know of no solid or liquid which refracts all the colours equally, and though the same colour which is most refrangible by glass is also most refrangible by water, oil, or any other

medium, yet, because the ratio between the refractions of the *most* and *least* refracted rays is not the same for every medium (75), we have the means of so combining two media as to refract all the colours equally. For instance, a certain kind of *plate glass* is found to bend the most refrangible violet rays always $\frac{1}{30}$ more than the least refrangible red rays. This is expressed by saying that its *dispersive power* is $\frac{1}{30}$, or 0·033. Suppose we have a kind of *flint glass*, which bends the violet rays $\frac{1}{20}$ more than the red, or has a dispersive power of 0·05. It is plain that, if we make a prism of each kind of glass, with such shapes that both shall bend the rays equally, say 30 degrees out of their direct path, both will not form spectra of equal length; for one spectrum will be $\frac{1}{30}$ of the whole refraction, or 1° long, while the other will be $\frac{1}{20}$ or $1\frac{1}{2}$° long. But let the two prisms have such shapes that, while one of them (the flint) refracts the ray 20°, the other (the plate glass) shall refract it 30°; then both will produce an equal dispersion of 1°. Consequently, if both be placed together in such positions as to refract in opposite directions (one 30° to the right and the other 20° to the left), the latter will not undo the refractive effect of the former, but will leave the ray still bent 10° to the right, and yet their dispersive effects, being each 1°, will entirely compensate each other; so that a refraction of 10° will be produced without any dispersion at all. The same principle is applicable to any other refracting instrument, such as a lens; and thus white or other mixed light is focalized without separating its component colours, and lenses are made to give an *achromatic** image as well as mirrors.

Experiments and computations without end have oc-

* *Achromatic* (from *α*, *not*, and *χρωμα*, *colour*), having none besides its proper natural colours; no rainbow-like fringes.

cupied opticians, ever since this discovery, to find what materials and what curvatures in the lenses of a telescope will render it most nearly *aplanatic*, or free both from the chromatic and all other errors. On the whole, refracting telescopes are now brought to greater perfection than reflecting ones, although they cannot be made so large.

77. We have seen, then, that the different qualities of light which we call *colours* all exist in common solar light, and are separated therefrom by virtue of their possessing different degrees of refrangibility, and also of absorbability by material media. The order of their refrangibility is the same in all media, but that of their absorbability is different in each medium. Some media have no preference for one quality of light more than another, but absorb them all equally; such are called neutral or colourless; the quality of *colour* in bodies is due to the preference they have for light of certain refrangibilities rather than others, so that the least absorbable rays are left either to be reflected from their surface, or transmitted through their substance to a greater depth than the more absorbable rays can penetrate; and in either case we name the colour of the body after that of these least absorbable rays. Thus, red glass is so called because it allows the red rays to penetrate through a greater thickness of it than the other rays; but at a certain thickness even the red rays would be all absorbed like the rest, and we should call the glass black. So, also, with the reflected colours of bodies which are generally (though not always) similar to the transmitted ones*.

78. That no body (unless self luminous) can appear of a colour not existing in the light that it receives will be

* There is a kind of glass common in the shops which transmits *orange*, but reflects *green* light; and another whose transmitted colour is *yellow* and the reflected colour *blue*.

abundantly proved by observing the appearances of coloured bodies held in the rays of the prismatic spectrum. It will be found that no such body can ever appear of a different colour from the rays that fall on it, though it may appear of any *shade* of that colour, even down to *black*, if it has not the property of reflecting any sensible quantity of light of this particular refrangibility. Thus the flower of a scarlet geranium held in the green rays and receiving no other light cannot be distinguished from black velvet.

Hence, if a room be illuminated with light of one definite refrangibility, all distinction of colour in that room will be lost and the most brilliant and variously coloured objects will all appear in mere *shades*, as in a drawing. Such light may be obtained from a lamp fed with a solution of common salt in alcohol. Now, if into a room so lighted there be thrown a few rays of common light, as, for instance, from a dark lantern with holes in it, the spots on which they fall will appear in their natural colours, like spots of bright colours sprinkled over an Indian ink drawing*.

79. It is doubtful whether any source of light, however, emits rays of only one definite refrangibility; generally speaking, it includes rays of every possible degree of refrangibility, within certain limits†; but in the above

* In such a light, the absence of all distinction of colour will not hinder us from performing all the most delicate offices of vision, as reading, working, drawing, or *shading* a drawing; whence may we understand how such operations are performed by those who have the singular defect of *colour-blindness*, or insensibility to differences of colour, as was the case partially with Dr. Dalton, the great chemical discoverer, who could only distinguish the fruit of a cherry-tree from its leaves by their form.

† A most remarkable exception to this is afforded by solar light, which, whether coming directly from the sun, or reflected by terrestrial bodies, the moon, or the planets, is always found to be deficient in certain rays of definite degrees of refrangibility, which degrees are not less than 600 in number, giving rise to what are called the *dark lines of the spectrum*.

case these limits are very narrow. In the light of other artificial sources they are wider, and widest of all in solar light, which includes not only all the colours visible to the human eye, but also rays both *more* and *less* refrangible than any that affect our optic nerve. These rays are accordingly invisible to us, and have only been discovered by their effects on other bodies. Those which are more refrangible than violet light are detected by their action on photographic preparations, and by producing other chemical changes, whence they are called the *chemical* rays. On the other hand, those rays which are *less* refrangible than any visible rays (even the red) have all the properties of *radiant heat* coming from bodies of a lower temperature than 800° Fahr. Such heat is less refrangible than red light, and we have already seen that common radiant heat, like common light, is a mixture of rays of various refrangibilities. Now, if the temperature of a radiating body be increased, it emits, in addition to the rays previously emitted, others of a higher refrangibility, till, when it attains the temperature of 800°, some few of its rays become as refrangible as the least refrangible rays of light, and accordingly become like them *visible*, and affect us with the same colour, so that the radiating body is then said to be *red*-hot. If it be heated more, it emits, in addition to the red, still more refrangible rays, viz., *orange;* then (at a higher temperature) *yellow* rays are added, and so on, till, when the body is *white*-hot, it emits all the colours visible to us; and in some cases (of very intense heat) even the invisible chemical rays, more refrangible than the violet, are emitted, though in less quantity than in the solar rays. Thus light appears to be nothing more than visible heat, and heat invisible light, their difference being only in the *degree* of certain qualities, and in the human eye being fitted to per-

ceive one and not the other, as the ear can appreciate vibrations more rapid than 16 in a second, and not less rapid ones.

80. Of the various rays composing solar light, the most visible to the human eye are the *yellow;* but those which have the greatest heating effect are the faintest red, or rather those *invisible* rays which are a little less refrangible than the red. Hence bodies which absorb the red rays become more heated by the sun than those which reflect them; *blue* cloth, for instance, becoming sooner hot than *red* cloth of the same depth of colour.

81. In the great majority of coloured bodies, each point reflects the same colour in all directions; but in some cases (as mother-of-pearl, soap-bubbles, &c.), each point may reflect different colours in different directions, and then we call the surface *iridescent.* Now, the doctrine of *absorption* is plainly inapplicable to these colours, which are often (as in the soap-bubble) seen in a film of matter infinitely too thin to exhibit its preference of some rays to others, even if it have any such preference, for it takes a thickness of many feet of water to exhibit colour from this cause. Moreover, the iridescent colours are more decided the thinner the film, and are not seen when it exceeds a certain thickness.

We have already mentioned (25) the means by which Newton investigated these colours of thinness, and measured the exact thickness necessary to produce each colour. He further ascertained that they are independent of the material of the film, and even appear when there is no such material, the only essential condition being the approach of two refracting surfaces within a certain minute distance.

By examining the colours through a prism, he found that they were in no case simple (or possessed of one

definite refrangibility), but that each iridescent tint was a mixture of certain rays of the spectrum, which rays *alone* were reflected by a film of this particular thickness, the remaining rays being *transmitted* by it, so that the transmitted as well as the reflected light is coloured, and the colours of the two are *complementary*, *i.e.*, each contains just what is wanting in the other to constitute white light. Any change in the thickness causes some rays that were before reflected to be transmitted, and *vice versâ*, so that whether the rays of any definite refrangibility shall pass through the film or be reflected depends entirely on its thickness.

Newton, therefore, examined these films (or the rings, Figs. 11 and 12,) when illuminated by rays of one colour only, instead of common mixed light, and he then discovered these astonishing facts, that if *red* light of a certain definite refrangibility pass through two surfaces whose distance apart is $\frac{1}{155000}$ of an inch, or $\frac{3}{155000}$, or $\frac{5}{155000}$, or $\frac{1001}{155000}$ of an inch, a great deal of it will be reflected; but, if the space between the two surfaces be $\frac{2}{155000}$, or $\frac{4}{155000}$, or $\frac{6}{155000}$, or $\frac{1000}{155000}$ of an inch, *none* of this light will be reflected. Again, light of another definite refrangibility will pass through without reflexion, only when the surfaces are $\frac{2}{160000}$, $\frac{4}{160000}$, $\frac{6}{160000}$, &c. of an inch apart, and will be reflected *most* when their interval is $\frac{1}{160000}$, $\frac{3}{160000}$, $\frac{5}{160000}$, or any other *odd* number of 160000ths; and each ray in the spectrum will be *most* reflected by these surfaces when they have a certain minute but measurable interval, or 3, 5, or any *odd* number of times that interval; but it will pass through them unreflected when they have 2, 4, or any *even* number of times that interval; and this interval is the same for all rays of the same refrangibility, but different for those which differ in that quantity, being always *shortest* for that ray which is

the *more* refrangible; and being only $\frac{3}{5}$ so long for the most refrangible violet rays, as for the least refrangible red ones.

82. An innumerable variety of other phenomena discovered since Newton's time have all concurred in establishing this wonderful fact—the *periodicity* of light; or, in other words, that the march of every ray of light through space is accomplished by equal and regular steps, the number of which in a given space is exactly measurable, though in different rays it has every possible value within certain limits. We may therefore identify a certain ray by the length of its steps. For instance, of the 600 definite rays which are missing from the solar spectrum (79, note), let us take the *seven* whose absence is most conspicuous. One of these is among the red rays, and it makes just 36,919 steps (or rather *paces*) in an inch; another is a green ray, and makes 48,289; another is violet, and makes 64,631 paces per inch. These are no matters of *theory*, but experimental facts. What the action may be which thus recurs at regular intervals in the progress of the light, we know not; but this we know demonstrably, that *an* action of some kind is repeated, at equal intervals, 64,631 times during the passage of this ray through an inch of space; but we also know that this action can pass through 192,000 miles of space in a second of time (62), whence it may easily be calculated (and we must believe, however little we may understand it,) that the action in question is repeated regularly 786,000,000,000,000 times in a second; that in the green ray a similar action recurs 587 billions of times per second; and in the red ray 449 billions of times; and that it is by distinguishing between these different rates of vibration (for any regularly repeated action may be called a *vibration*) that the optic nerve distinguishes colours.

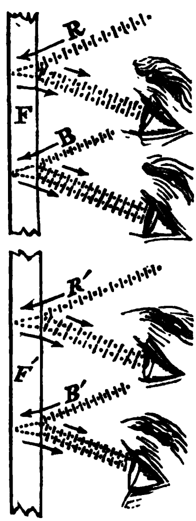
The velocity of all rays being equal in vacuo *, it follows, that white light may be compared to a crowd of men and children all running with the same speed, but with steps of various lengths, the *shortness* of the steps of violet light being compensated by their *frequency*. But, when any ray enters a medium, its number of steps per inch is increased in the ratio of 1 to the refractive index of that medium for this particular ray. Thus, as the *time* occupied in performing a step must remain unchanged, while the length of step is diminished, it follows that the progress of the ray must be *slower* in the medium than in vacuo. Moreover, those media which refract the different rays unequally must *retard* them unequally, so that in solids and liquids their velocity is no longer quite equal, but the red travel a little the fastest, and the violet slowest, this difference being greatest in the most *dispersive* media.

83. It is proved mathematically, that all the effects of refraction are simple consequences of this *retardation*, which is a law of a more general order, and is proved by numerous phenomena where there is no refraction. All the phenomena of iridescent or *periodical* colours were first generalized by Dr. Young, who proved by direct experiment this most singular fact, that when two rays of light of the same refrangibility (or length of step) travel together, or fall on the same spot of the optic nerve, they do not double each other's effect unless their steps correspond, but if (while they keep correct time) their steps are *reversed*, like those of ill-trained

* As sound of all qualities, so light of all colours, travels with the same speed, at least in air. Otherwise, the *aberration* (62) being different for each colour, every star would appear lengthened into a spectrum in the direction of its aberration. Nor is this equality confined to our atmosphere, but extends throughout the solar system; otherwise Jupiter's satellites would appear to change blue or red just before their eclipses, and assume the opposite colour on their reappearance.

recruits, they absolutely (if of equal intensity) *neutralize* each other, and double light produces darkness, just as double sound produces silence in the phenomena of *beats*. However at variance this may seem with common experience, it is found to be strictly true as regards *single rays* having one definite direction and refrangibility, though lost sight of in the heterogeneous mixture of all sorts of rays, pencils, and beams, which meets us at every turn. The *direct* proofs of this *interference* of light, therefore, require considerable care and nicety, but numberless indirect proofs are afforded by the perfect manner in which it explains all the phenomena of iridescence.

Fig. 32.



As we have twice alluded to the colours of thin films, we will again choose this example, as showing one of the simplest applications of the principle of interference. Let F (Fig. 32) represent such a film, on which common light is falling in the direction of the lines R, B, and let R be supposed a ray of *red*, and B a ray of *blue* light, the periods or paces of the latter being shorter than those of the former. A portion of each ray is reflected without entering the film, the rest enters it, is reflected from its back surface, and emerges again, and, though twice refracted by the front surface, it will obviously emerge parallel with the former portion; but, as it has lost a few steps in travelling twice through the film, its steps may or may not correspond with those of the first portion. In the case of the ray R they do not correspond, while in B they do,

simply because the latter ray took an exact number of paces to travel twice through the film, while R took an odd number of half paces. Thus it appears that a film of this thickness will appear blue, because all the red rays reflected from it destroy each other, while all the blue reinforce each other, at least when the rays fall at this angle (and the colour of such film varies with the angle of sight, as well as with the thickness). But by a very slight change of thickness, as at F′, the contrary may take place, the red ray R′ making an *even*, and the blue ray B′ an *odd* number of half paces in twice traversing the film, so that the former will *reinforce*, the latter *destroy* each other, and the apparent colour of the film will contain more red than blue.

84. The phenomena of interference plainly indicate that the periodically repeated actions constituting light are alternately *opposed* to each other, otherwise they could not effect their mutual destruction. Hence the intervals of space at which they recur are called *waves* of light, in precisely the same sense that we speak of waves of sound (15, 44); which by no means implies that the action must *resemble* that of sound, any more than the latter resembles the undulation of water, or of a corn-field, or of a shaken carpet, all of which are totally different actions, though all alike constitute *waves*, because this is a general name for any alternating motion (or vibration) propagated from place to place*.

As a *musical note* may be produced by the reflexion of a common non-isochronous *noise* from a large number of parallel equidistant surfaces (45), so may colour be produced by the reflexion of *colourless* light from a

* The facts now under consideration are totally unintelligible by regarding light as matter; for two material particles cannot annihilate each other, as two rays of light do, and as two forces or motions can.

similar set of surfaces. An exceedingly fine grating, or a set of parallel grooves or other lines, so near together as not to include *many* waves of light, produces iridescent colours. Mother-of-pearl owes its appearance to this cause, it being composed of distinct laminæ, so that any artificially ground surface cuts them all obliquely, and exposes their edges like those of the leaves of an open book, forming regular grooves, of which there are several thousand in an inch. That the colours depend on this configuration of surface will be plain by taking a cast of it in wax, which will display the very same iridescence as the original.

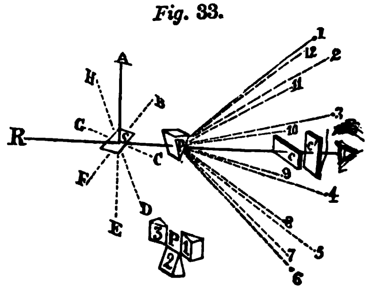
85. Our limited space will only admit of a very brief notice of the last general property of light, namely, its *polarization*. If a round hailstone drop upon the sloping roof of a house, it will act, as regards its rebound, just in the same manner whether the slope be towards the north, south, east, or west. But this will not be the case with an *arrow* under the same circumstances, because it has a *distinction of sides*, and its behaviour will vary according as the plane of its barbs is parallel with the eaves or with the rafters of the roof, or inclined to both. A bullet in its flight from a gun has also *sides to its motion* (though not to its *form*), because it revolves on an axis, which may be vertical, horizontal, or inclined; but, if shot from a *rifle*, it has no such sides, because, though spinning on an axis, that axis has, by a particular contrivance, been made to coincide with its line of motion, so that it presents the same aspect above, below, or on either side. Now, if these projectiles were too small or too rapid for us to discover the reason of these differences, we might still observe the differences themselves, and should express them by saying that the motion of the arrow or the gun bullet possessed *polarity*, or *polarization*, which

was not the case with that of the hailstone or the rifle bullet. Polarity, then, means simply a difference of sides.

That a ray of light should (in some cases) possess this property is not perhaps so wonderful or unexpected as that man should have been able to detect a fact so refined and remote from common observation, and even to distinguish different varieties of it, and investigate its laws. Indeed, these must be regarded as the very *penetralia* of physics, the very inmost secrets of nature that man has been enabled to wrest from her. If the *measurable* spaces occupied by the *waves* of light be minute, how far less, in all probability, must be those *immeasurable* spaces to which its vibrations are confined (which even in sound are mostly inappreciable, though the waves occupy many feet); yet it is to the positions of these inconceivably minute vibrations that the differences of polarization are due *.

These differences are not sensible to the eye, but are arrived at by inductive reasoning from such facts as the following. Let R (Fig. 33) represent a ray of light, which in its progress meets (obliquely) with the surface S; a portion of it will be transmitted, and the rest reflected in the direction S A. Now, by making S revolve round an axis coincident with the ray R S, we may obviously reflect it in various di-

Fig. 33.



* Differences of *intensity* depend on their extent; differences of *colour* on their frequency; differences of *polarization* on their form and direction.

rections successively, as S B, S C, S D, S E, S F, S G, S H, all making equal angles with the original ray R S; and, if this be destitute of polarity, there is no reason why it should behave differently when reflected in these different directions, nor will a direct ray from any luminous source do so. The reflected light will bear the same proportion to the transmitted in each case; so that all the rays S A, S B, &c. will be of equal intensity. But if we find that they are *unequal*, the transmitted ray being *brighter*, and the reflected one *fainter*, when the latter is turned in the directions S B and S F (for instance), than in the directions S D or S H, we have distinct proof that this light has *sides*, or is *polarized*.

86. Or suppose we turn the ray aside by *refraction*, as by a prism P. By turning this prism round so as to take successively the positions shown in the lower part of Fig. 33, at P 1, 2, 3, we may plainly turn the ray upwards, downwards, or sideways, in any of the directions *p* 1, *p* 2, *p* 3, *p* 4, *p* 5, *p* 6, *p* 7, *p* 8, *p* 9, *p* 10, *p* 11, *p* 12 (the refraction in each case being equal). Now, if it behave differently in these cases; if, for instance, it be refracted doubly, or split into *two* rays of *equal* intensity when turned upwards or downwards, and into two of *unequal* intensity when turned to the right or left, its polarization is thus manifest.

87. Or again, if the eye receive this ray through a plate of some transparent substance *c*, and if more light penetrate this plate when it is held upright, as at *c'*, than when held across as at *c* (though in both cases perpendicular to the ray), we plainly learn from this not only the polarity of the *light*, but also that of the substance *c*, which must evidently possess a *grain* or polarity of texture, a difference of properties in different directions; and accordingly this action on light is perceived only in *crystallized* bodies, or those which, from

the action of their molecular forces, assume certain definite geometrical forms, and whose *polarity* is also manifest in many other ways, as by their splitting in certain directions rather than others, their expanding by heat unequally in different directions, &c., &c.

The laws of the polarization of light form a distinct science of vast extent and beauty; for, though this property (first observed by Newton) was never experimented on till the present century, yet during this short time discoveries have thickened, and have *led*, step by step, to higher and higher generalizations, till at length the late French mathematician, *Fresnel*, was enabled, by a magnificent theory, to bring all these complex and wonderful phenomena under *the* simple laws of mechanics, and by the composition and resolution of forces, not only to explain all the phenomena then known, but to predict others the most startling and unexpected, and which have as yet been verified without an exception.

88. Perhaps the most important rule respecting *polarization* is, that light coming directly from a source, as the sun or a candle, *never* possesses this property, while that which has been reflected *always* possesses it more or less. It is very singular that a ray once polarized retains that property during all its subsequent course, whether that be for inches, miles, or billions of miles. Thus, with no other apparatus than a fragment of a crystal, we may examine the polarizing effect of the far distant surface of the planet Saturn as readily as that of the page before us. We may ascertain whether a star at the outskirts of the visible universe shines by its own or by reflected light. In this way Arago has proved that, in some of the binary systems, the two stars are two suns, while in others the smaller is only a vast planet reflecting the light of the larger. In this extraordinary observation we

cannot fail to be struck with the great disproportion between the means of observation and the fact observed,—and especially with the astounding universality of this agency, light, which at once pervades galaxies and penetrates between atoms.

89. The polarity of light leads us naturally to consider next those effects depending on the polarity of *matter*, or of its ultimate particles; for this is a general principle, towards which all physical discoveries seem now to be conducting us. Some of the modes in which this polarity is displayed by *crystals* have been alluded to (87). Crystals appear to differ from other bodies in this,—that their particles are so arranged as to have all their similar polarities in the same direction. The investigation of the laws regulating their *forms*, *cleavage* (or facility of splitting in certain directions), *refraction of light*, *polarization*, and *unequal expansibility* in different directions by heat, presents an infinite field of research, which has occupied the attention of some of the greatest philosophers since Huygens and Newton first elucidated the laws of refraction.

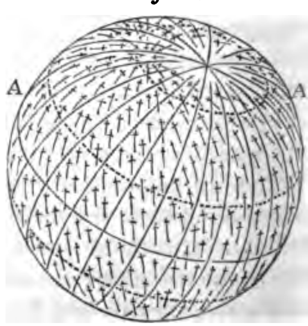
90. But polarity is displayed in perhaps the *most* striking manner by the phenomena of *magnetism*, a property which, by certain processes, can, as it were, be superadded to the other properties of iron and steel without in any way affecting those other properties.

The property of magnets most familiarly known, that of attracting common iron, is not spread over the whole surface of a magnet, but is strongest (in artificial magnets) at their two *ends*, and altogether absent in the middle. But there is also an *opposition* in the properties of the two ends; for, although both attract common iron alike, they do not both attract a particle of magnetized iron, for, on presenting them to the poised magnet or *needle* of a compass, each end attracts only

one end of the needle and *repels* the other. If we take two magnets, and mark one end of each in such a way that both their marked ends have the same action on the needle, we shall find that these magnets manifest towards each other no *attraction* except between a *marked* end of one and an *unmarked* end of the other, while between *two marked* or *two unmarked* ends there is a repulsion.

91. This is the most important law in magnetism, and on it depend all the effects of *terrestrial* magnetism, or the tendency of the needle towards particular parts of the earth (so invaluable by its direct application to our wants); for all these effects indicate that the earth herself acts as a great magnet, having her two magnetic *poles*, or centres of attraction, not far from her poles of rotation; the northern being near Hudson's Bay, at a spot reached by our arctic voyagers, and the southern in the newly discovered continent of Victoria Land. As these spots are not, however, identical with the true poles or ends of the earth's axis, the needle does not (at most places) point to the true poles, as will be evident from Fig. 34, which represents compass needles distributed over the globe, all lying in the direction of lines drawn from one magnetic pole to the other (only one can of course be seen in the figure), which lines are called *magnetic meridians*, and obviously do not coincide with the true meridians (represented by black lines) except at a few places, such as A A. Elsewhere there is a magnetic *variation*

Fig. 34.



or declination of the needle from the true meridian, which variation amounts, in London, at the present time, to about 23° west of north (or east of south), and its determination in other places throughout the globe is of the utmost importance to navigation. Owing to the irregular distribution of the magnetic force in the earth (as in all other loadstones or *natural* magnets), the variation at any spot cannot be calculated by knowing its position and that of the magnetic poles; for the line at which there is *no variation* (as at A A) is not, as might be supposed, an exact circle passing through both the true and both the magnetic poles, but an *irregular* circle, of which the eastern half passes through Siberia, China, and Australia, and the western half returns from the south pole through Brazil, across the islands of Jamaica and Cuba, and so through the United States to the north magnetic pole near Hudson's Bay. The farther a needle may be from this line, the greater its variation.

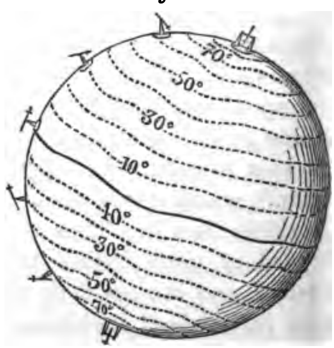
92. But there is no magnetic element, not even the position of the poles, which does not constantly, though slowly, vary. Hence the direction of the needle at every spot is gradually changing, as the magnetic poles and line of no variation slowly revolve round the globe from east to west. In 1659 this line passed through England, which is now about 90° of longitude, or as far as possible from it. Thus the variation here, which was eastward of north before 1658, has ever since been westward, and increased up to 1816, since which it has slowly diminished, indicating that we are now rather nearer the Siberian than the American branch of the line of no variation.

93. The needle also makes reciprocating movements of very small extent daily, monthly, and yearly, for observing which *magnetic observatories* have been built

and are constantly attended. They have disclosed the remarkable fact of its undergoing also sudden and irregular disturbances, which have been called *magnetic storms*, and are found to occur at the same instant all over the globe.

94. The laws of terrestrial magnetism are also well illustrated by the *dip* of the needle, or the tendency of one end to preponderate, though it were exactly balanced before being magnetized. In this country the *north* end dips about 68° from the horizontal line, being more strongly attracted by the earth's north pole than the other end by the more distant south pole. Hence it may easily be concluded that a *dipping needle*, or a needle poised on a horizontal axis placed east and west, instead of a vertical pivot, will, when carried to either of the earth's magnetic poles, stand *upright*, the end which is upward at one pole being downward at the other. The further we recede from either pole, the less does the needle dip, as shown in Fig. 35, where the dotted lines represent the lines of equal dip, or parallels of magnetic *latitude*. The magnetic *equator*, or line of *no dip*, where the needle, balanced between the actions of both poles, rests horizontally, is not coincident with the true equator, but nowhere deviates more than 12° from it.

Fig. 35.



95. The *intensity* of the magnetic force is greatest at the poles and diminishes towards the equator, and *both* the dip and intensity are (like the direction) subject

to daily, monthly, and yearly variations, and sudden storms.

96. Magnetism is not peculiar to iron and steel, though incomparably stronger in them than in other bodies. It was proved by Coulomb, and has lately been confirmed by Faraday, that no substance in nature is quite indifferent to the influence of a very powerful magnet, but with this distinction; very few bodies besides iron can be made to display magnetic *polarity*, that is, both attraction and repulsion. The great mass of substances either exhibit *attraction only* (like unmagnetized iron), or else (which is more common) *repulsion only;* being equally repelled from both poles of the magnet. The former have been classed by Faraday as *magnetics*, the latter as *diamagnetics*. This great experimentalist has also detected the *action of a magnet in modifying the polarity of light.*

97. Closely connected with magnetism (though by unknown ties) is that widely spread, apparently universal, description of polarity called *electricity*. If we rub a long glass tube briskly with a dry silk handkerchief, a slight crackling noise will be produced. In the dark the tube will appear faintly luminous, and if the finger be held to it a small spark will be seen to pass from the tube with a slight snapping noise. This luminous appearance is *electricity;* the spark is called the *electric spark*, and the tube is said to be *electrically excited.* On presenting the excited tube to a couple of light downy feathers, suspended from the ends of a long piece of silk thread, they will be attracted by and adhere to it. On gently withdrawing the tube, they will not hang down loosely as before; they will *repel* each other; and on again presenting the excited tube, they will be still further repelled. But on leaving them undisturbed for a time, the air will gradually rob them of

their electricity, and they will hang together as at first.

In this experiment, when the feathers are adhering to the glass, they rob it of a portion of its electricity, by which action both become *similarly* electrified, and they repel each other. The glass tube also, being electrified like the feathers, also repels them. Hence we learn that *bodies similarly electrified repel each other.*

98. If, instead of the glass rod rubbed with silk, we rub a stick of resin with a piece of warm, dry flannel, similar effects will be produced; nor does there appear, from these results, to be any difference between the electricity of glass and of resin. But if, while the feathers are being repelled by the glass, we bring near them the excited stick of resin, they are no longer repelled, but attracted. Or if, while the feathers are being repelled by the resin, we bring near them the excited glass tube, this will attract them. Hence we learn that the electricity of glass must have a property different from that of resin, because one attracts what the other repels. Now, these opposite polarities have received the names of *vitreous* and *resinous*, or *positive* and *negative* electricity; the one being produced from glass and vitreous bodies, and the other from resinous bodies. We learn, also, that bodies *dissimilarly electrified attract each other.*

99. Let us now examine the substances used to excite the glass and the resin. If, when the feathers are repelled by the glass, we bring near them that part of the silk handkerchief used to excite the tube, the feathers will be attracted by the silk. Remove the silk, and present the glass tube, and they will be repelled. Or conversely, when the tube has been excited by the silk, present the silk first to the feathers, and they will be first attracted and then repelled. If, while in this state of repulsion, we bring the excited tube near them, they

will be attracted by it. Similar results may be obtained with the resin and the flannel. We see, then, that in rubbing glass with silk, or resin with flannel, both kinds of electricity are developed; and it appears that *one kind of electric polarity cannot be produced without the production also of the other kind, either in another part of the same body, or in distant bodies**.

100. It is probable that similar effects might be produced with any solids properly rubbed; but in many substances the electricity disappears as fast as it is formed. We cannot, for example, excite a rod of metal like the glass tube, by holding it in the hand and rubbing it. If, however, the metal rod have a glass handle, it can then be excited, and will retain its electricity. Hence bodies are arranged into two classes, *conductors* and *non-conductors*, or *insulators*. Metals are the best conductors, because electricity travels along them with the greatest facility. The glass tube and the silk thread are called *non-conductors*, because electricity travels along them with difficulty. The bodies in which electricity is excited are called *electrics*, and in general the best electrics are the worst conductors, and *vice versâ*.

101. Electricity must have remained for ever unknown were it not that dry air is a good insulator; for the electric polarity (of either kind) has, like heat, a constant tendency to diffuse itself, and that not slowly, but *instantaneously*, unless completely surrounded by

* Herein electricity resembles, and also differs from, magnetism; it resembles it because neither kind of polarity can be produced alone; it differs from it because the magnetic polarities are so inseparable that both must exist in the *same body*; for if we break off one end of a magnet, the piece broken off will not be a single pole, but a perfect magnet having two poles, no magnetic body, however small, possessing one polarity without an equal intensity of the other; whereas the electric polarities can be separately accumulated in different bodies, as in the glass and silk, or the resin and flannel.

insulators. Moreover the two polarities are capable, by their union, of totally neutralizing each other; so that a communication opened between two oppositely electrified bodies instantly reduces both of them to their naturally electrified state. While separated by an insulator (such as air) they manifest a tendency to communicate, not only by their mutual attraction, but by the polarity of each being intensely concentrated on the side next the other. When they approach within a certain distance, called their *striking distance* (which is greater or less according to the intensity of their excitement), the intervening insulator is instantly broken through or burst asunder, with an evolution of heat, light, and sound, which is called the *disruptive discharge* or *spark*, and in nature, *a flash of lightning*. If the two bodies be good conductors, this discharge instantly restores both to their natural state, or, in other words, restores electrical equilibrium.

102. When two conducting surfaces are separated by an insulator, the accumulation of either the positive or negative polarity in one surface will develope the opposite polarity in the other by a peculiar action called *induction*, which is entirely the reverse of *conduction*, inasmuch as it takes place only through *non-conductors;* and instead of tending to restore equilibrium, has just the opposite tendency to increase its disturbance, or widen the difference between the two polarities by rendering both more intense.

103. The usual method of accumulating electricity is by means of the *Leyden jar*. This is a glass bottle, coated on both sides with tin foil, except a portion of the upper part of the jar. The mouth of the jar must communicate with the inside by a metallic conductor, with a knob at its upper end, its lower end being in contact with the inner metallic coating. In this arrange-

ment we have two metallic conducting surfaces separated from each other by the non-conducting glass. It is evident that we can bring the two coatings into connection by placing a metal wire against the outer coating, and also against the knob at the top of the jar. On presenting the knob to the electrical machine, sparks of vitreous or positive electricity will pass into the jar, which becomes vitreous or positive, and, by *induction* through the glass, renders the outside resinous or negative; and the mutual attraction of the two polarities retains them in the coatings, or rather on the two surfaces, of the glass which separates them, and which is then said to be *charged.* If we make a metallic communication between them, the two electricities instantly neutralize each other (101); a brilliant spark of light passes between the knob of the jar and the metal used to make the connection. It is the duration of this spark and the velocity of its transit which is now to be considered; but in order to arrive at a distinct idea of the principle on which this wonderful measurement is based, we must gradually approach the subject by introducing a familiar experiment.

104. Every one is aware that when a lighted stick is whirled rapidly round, the effect on the eye is that of a continuous ring of fire. Let us suppose that the end of the stick describes a complete circle in $\frac{1}{10}$th of a second, and that we keep the eye fixed at one point of the ring. When the lighted stick is at this point the rays of light proceeding from it form an image in the eye of the observer upon a certain part of the retina. It might be supposed that, as soon as the stick had passed this point, this image on the retina would disappear, and another be produced on an adjoining spot of the retina, answering to the new position of the stick. But though the new image appears, the former does not vanish, for

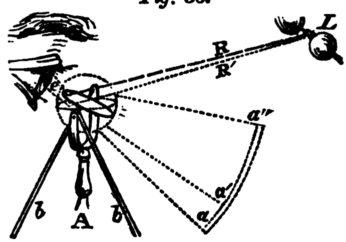
the stick has time to make an entire circuit and return to its former position to reproduce this image before the sensation resulting from its first transit is effaced. Thus it appears that a luminous impression made on the retina has a certain persistence, and we may conclude from the above experiment that it continues at least one-tenth of a second after the cause which produced it has ceased. If, then, a luminous point, moving through the circumference of a circle in the tenth of a second, produces on the eye the effect of a complete *ring*, it is evident that a line of light revolving round one of its ends as a pivot, ten times per second, will appear as a complete luminous disc. But let us suppose that, instead of one line of light, there are 10, 100, or 200 luminous equidistant radii, it is evident that the velocity of rotation may be 10, 100, or 200 times less than in the case of a single luminous radius. Or if a small wheel, with 100 equidistant spokes, be illuminated by the light of a lamp, this wheel need only perform one revolution in ten seconds in order to appear as a complete luminous disc.

But let us take a greater speed, and suppose the 100 spokes to make a complete revolution in the $\frac{1}{10}$th of a second. Each spoke would then pass through the space which separates two spokes in the $\frac{1}{100}$th of the $\frac{1}{10}$th of a second; that is, each spoke shifts its place into that of its advancing neighbour every $\frac{1}{1000}$th of a second. Bearing this in mind, let us next suppose that the light by which we see the wheel does not shine continuously, but flashes upon it for less than the $\frac{1}{1000}$th of a second. The wheel cannot then appear as a complete luminous disc, because the spokes have not time to replace each other during their illumination, so that 100 dark spaces will be left, and the proportion which they bear to the whole area of the wheel will show us how much the duration of the flash fell short of $\frac{1}{1000}$th of a second.

If we suppose the light to continue only a very small fraction of $\frac{1}{1000}$th of a second, the spokes will not have moved through any appreciable space, and the wheel will appear precisely the same as when at rest, although the impression will remain on the retina the $\frac{1}{10}$th of a second. This is what takes place when the rotating wheel is illuminated by a flash of lightning, or by the discharge of a Leyden jar, and however we may increase the number of spokes in the wheel, or the rapidity of its rotation, the light has come and gone before the wheel has had time to turn through a sensible space. A revolving disc, on which any object is painted, seems perfectly stationary when illuminated by the explosion of the Leyden jar. Insects on the wing appear by the same means fixed in the air, and vibrating strings are seen as if at rest in their deflected position.

105. Professor Wheatstone, to whom these beautiful experiments are due, finding that he could not obtain sufficient speed by this means to measure the duration of a flash of lightning, invented a revolving mirror, Fig. 36, where A is a support bearing a plane mirror turning on a horizontal axis, like a little swing dressing glass, and made to spin rapidly by the endless strap *b b* passing round a large wheel below. On looking into this spinning mirror, we receive rays reflected by it from any fixed light, as a candle at L, during only a small part of its revolution, more or less according as the eye is nearer or farther from the mirror Suppose now that when the mirror has the position shown in the figure, we see the light in the direction *e a*;

Fig. 36.



when the mirror has attained the position shown by the *dotted* oval, we shall see the same light in the direction $e\,a'$, the angle $a\,e\,a'$ being *twice* that moved through by the mirror. As the mirror turns we shall see the light apparently describe the arc $a\,a'\,a''$, the apparent length of which (or the angle $a\,e\,a''$) depends on our nearness to the mirror. Suppose we look close enough to see this arc 40° long, then we see the light during the motion of the mirror through 20° or $\frac{1}{18}$th of a revolution; and it will be obvious that, if this motion occupy less than $\frac{1}{10}$th of a second, we shall *see* the light in every part of this arc at once as a band of fire; and if the mirror make one revolution in less than $\frac{1}{10}$th of a second, this band of fire will be seen continuously, though its image is only impressed on the eye during $\frac{1}{18}$th of each revolution. Now, let the light L be an electric flash. If it last during less time than it takes the mirror to move through 20°, we plainly cannot see the whole arc of 40° at $a\,a''$, for the light does not last long enough to be seen successively at every part of that arc. The less its duration, therefore, the less of the arc will its image be spread over, and by observing its angular elongation we can at once calculate its duration, provided we know the rate at which the mirror is spinning. This Professor Wheatstone ascertained by the *notes of a syren.* He found that when the mirror revolved fifty times in a second, an electric spark appeared in the reflexion exactly as in the reality, or was not elongated through any perceptible space. Now, an elongation of half a degree would be plainly perceptible (being equal to the moon's diameter, or an inch seen at 10 feet distance), and this would have indicated a duration while the mirror moved through 15′. But it moved through 360° in $\frac{1}{50}$th of a second, therefore through 15′ in $\frac{1}{72000}$th of a second, and the duration of the spark was *less* than this.

By increasing the speed of the mirror, however, he at length succeeded in making the spark appear, in some cases, *elongated* to a measurable extent, and, by the simple method of calculation above exemplified, he found that though its duration varied greatly under different circumstances, yet it never *exceeded* a *millionth of a second.*

106. But far more astounding was the discovery by the same means of the speed of transference of the electric force through a copper wire. Professor Wheatstone made the two coatings of a Leyden jar communicate through *half a mile* of wire, interrupted at three places, namely, near the two coatings, and at its centre, ¼ of a mile from each, and so arranged that these sparks might be seen together, side by side. Of course the centre spark must occur later than the others, by the time which it took the electric impulse to travel through ¼ of a mile of copper. Now, when viewed in the mirror, these sparks were seen *elongated* alike, but until he made the mirror revolve at the extreme speed of 800 *turns per second,* he could not perceive that the central spark appeared the least degree higher or lower than the others; its foot and top appeared level with them, as if it began and ended at the very same instant. With the above extreme speed, however, he did perceive a slight difference, much less than the elongations of the sparks themselves, indicating that their duration was much longer than the passage through the quarter mile of wire, which occupied no more than the 2,304,000th of a second. This is at the rate of very nearly *three times* that of light through planetary space.

107. The science of electricity necessarily leads the student into the domain of *Chemistry,* where it is not our business to enter. It may, however, be desirable to endeavour to form a clear idea of the precise dis-

tinction between *Natural Philosophy* and *Chemistry*. The distinction is becoming every day less precise, for it is no longer possible to divide the book of nature into volumes, and sections, and chapters, and deal them out to separate students for examination and interpretation; for one student finds that he wants something which another student has taken away, so that they must either work together, or each must have his own separate and complete copy of the book, and meet together from time to time to explain and compare the results of their labours. Still, however, there are certain distinctions which may assist the student in understanding the object the natural philosopher has in view in contradistinction to that of the chemist. These distinctions may be considered under three heads:—

First. There is a necessary *generality* in physical researches and a necessary *speciality* in chemical researches. Physical properties are similar in different bodies; chemical properties are similar only in the same body. For example, the phenomena of weight are displayed in the same manner in all bodies; they are similarly affected by heat; they are all more or less sonorous; and they all exhibit optical, magnetic, and electrical phenomena. Whatever differences are observed are only differences in degree. Glass is said to be transparent because it transmits light with facility; gold is said to be opaque because it stops the passage of light; but glass if thick enough would be opaque; and by hammering gold into an exceedingly thin leaf it becomes transparent, or at least translucent. Bodies have been divided into conductors and non-conductors of electricity; into electrics and non-electrics. All bodies, however, conduct electricity more or less freely, and by peculiar contrivances (100), bodies called non-electrics may be made to develop electricity.

But in the different compositions and decompositions with which the chemist has to deal, *specific* properties are brought out at every turn, and these vary not only among the different elementary substances, but also among the most analogous compounds. For example, the atmospheric air is composed essentially of two gases, oxygen and nitrogen, which are *mechanically* mixed in the proportion of 4 volumes of nitrogen to 1 of oxygen, and with this constitution, and in this proportion, atmospheric air is the support of animal and vegetable life, and of combustion. Combine these gases *chemically*, (*i.e.* more intimately than by mere mixture,) and in different proportions, and we get totally new bodies. 14 parts by weight of nitrogen, combined with 8 parts by weight of oxygen, produces a gas (the nitrous oxide) which has a faint agreeable smell; is absorbed by cold water to the extent of about three-fourths of its volume; mixed with hydrogen, and ignited, it explodes; bodies burn in it with increased brilliancy, and when taken into the lungs it produces a sort of intoxication, generally accompanied by convulsions of laughter. 14 parts of nitrogen with 16 parts of oxygen produce a gas, the nitric oxide, which has totally different chemical properties. Cold water scarcely absorbs it; mixed with hydrogen it burns with a green flame; a lighted taper will not burn in it; any attempt to breathe it produces suffocation, and when let out into the air it becomes of a reddish brown colour. 14 parts of nitrogen combined with 40 of oxygen form nitric acid, a corrosive poison, and one of the strongest of acids.

Hence the distinction between *mechanical* and *chemical* union or combination is that, in the former, the compound has in every respect properties intermediate between those of its ingredients; it is heavier than one and lighter than the other, (we speak of

specific weight;) more transparent than one, more opaque than the other; harder than one, softer than the other, &c., &c. But a *chemical* compound has properties not intermediate between its ingredients; it may be harder than either, more transparent than either, specifically heavier than either, and, in fact, often has no one property in the degree that could have been calculated from *their* degrees of it, except *absolute weight* (which is invariable), and, perhaps, *refractive power*. Whenever combination, then, produces a change of properties (or of any one property), the phenomenon is referred to chemistry; whenever there is no such change it is referred to physics. This is the only distinction.

Physical differences in bodies are always to be detected by the senses of *touch*, *hearing*, or *sight*. Chemistry deals with such differences as are only sensible to *taste* or *smell*, or by the action of bodies on each other. A physical difference between two bodies does not necessarily imply a chemical difference, for *ice* and *water*, or *charcoal* and *diamond*, though physically different, are chemically the same; while, on the other hand, *strontia* and *baryta*, *nitrogen* and *carbonic oxide*, present examples of bodies physically alike, but chemically different.

Secondly. The old distinction between natural philosophy and chemistry was, that the phenomena examined by the former related to *masses* of matter, and the phenomena of chemistry to *molecules*. This distinction is not worth much, because many physical phenomena are purely molecular, such as cohesion, adhesion, elasticity, and the various kinds of polarity. Indeed, physical phenomena as observed in masses are but sensible results of molecular actions, which, taken individually, would be insensible as far as the modes of investigation placed at the disposal of the natural

philosopher are concerned. But a certain mass or volume of any substance is equally necessary for the display of chemical phenomena; so that the distinction between masses and molecules does not form a real distinction between natural philosophy and chemistry. It is often necessary, however, for the exhibition of chemical phenomena, that substances intended to act upon each other should be brought to a state of minute division. Thus, the metals iron, copper, and lead, in masses, resist the action of the atmosphere; they become slightly tarnished with oxides, which protect them from further action; but in a state of minute division they are acted upon with great energy, and often present the phenomena of combustion by simple exposure to the air. It is also often necessary for the exhibition of chemical phenomena that one of the bodies should be in a fluid state. Solutions mostly depend upon this condition, and here again a state of minute division is important, merely by increasing the surface of contact between the solvent and the body to be dissolved; thus offering an immense number of points where the action may simultaneously be exerted. It is obvious that the conditions of comminution and fluidity are never indispensable in the production of physical phenomena properly so called.

The *third* and most important distinction between natural philosophy and chemistry is, that in physical phenomena the constitution of the body, or the mode of arrangement of its particles, may be changed, although, in general, it remains unaltered. Yet the arrangement of particles in sugar may be altered without altering any chemical property, but only the physical property of polarization; but its nature, or the *composition* of its molecules, remains constantly unalterable. In chemical phenomena, on the contrary, not only is there always a change of state with respect to one of

the bodies under consideration, but the mutual actions of these bodies necessarily change their nature, and it is this very change which constitutes the chemical phenomena. For example, a mixture of magnesia and water produces almost no chemical change; their combination is almost purely mechanical; the water dissolves less than a six-thousandth part of this earth, so that by passing the mixture through a filter, the water and the magnesia can be almost perfectly separated. If, however, we add magnesia to dilute sulphuric acid, a solution, or true chemical combination, takes place. Twenty parts of magnesia combine with 40 of sulphuric acid and 63 of water to form 123 parts of sulphate of magnesia, a crystalline salt, soluble in its own weight of water at 60°, and of a nauseous bitter taste. In fact, we get a new compound whose chemical properties are totally different from those of its component parts. The acid is intensely sour and caustic, the earth is insipid and slightly alkaline; combine the two and we get the well known Epsom salts.

This example leads us to a specific difference between a mechanical or physical phenomenon and a chemical phenomenon. In the one we get the *mean* of the properties of the component parts; in the other we get *different* properties. In the one we still recognise the distinctive properties of the two bodies brought together; in the other we have to study the properties of a third substance.

Hence if all chemical phenomena should eventually be found to depend on physical agencies, it will still be necessarily true, that in a chemical fact there will always be something more than in a physical fact, namely, a characteristic change in the molecular condition of the body, and consequently in all its properties. Hence *Natural Philosophy* is the science in which we study the laws which govern the general pro-

perties of bodies viewed in the mass, and constantly placed in circumstances susceptible of preserving untouched the composition of their molecules, and even most commonly the state of their aggregation.

108. Should the young student who has followed us through this hasty sketch seek in vain for the moral of our story, and ask, "What is the use of Natural Philosophy?" we may reply by quoting Franklin's answer to a similar inquiry, "What is the use of a new born infant?" The germs of all scientific research contain the elements of future strength and usefulness. All our knowledge bears reference either to *speculation* or to *action*, and hence may be divided into the *theoretical* and the *practical*. The first constitutes the natural basis of the second, and every branch of industry has derived inestimable benefit from scientific theories. Who could have supposed that the ancient Greek geometers, while speculating on the properties of the conic sections, would be of infinite service, after a long series of ages, in renovating the science of astronomy, and bringing the art of navigation to a perfection which it would probably not have attained in our own day, but for the purely theoretical labours of Archimedes and Apollonius; so that, as Condorcet beautifully remarks, "the sailor who has been preserved from shipwreck by an accurate observation of the longitude, owes his life to a theory conceived two thousand years ago, by men of genius who had in view only simple geometrical speculations." Hence we must never test the value of scientific discoveries by their practical application. If not applicable now, they may become so hereafter, as the whole history of science proves. It is enough for us that our highest intellectual capacities are trained and gratified by the study of natural laws, because, in proportion as we master them, we gain power over the

material universe. Our knowledge, it is true, proceeds by slow and painful steps; it is constantly obscured by error, doubt, and difficulty; but there is this cheering influence connected with studies of this kind, that the more we know, the less we have to remember; for in proportion as knowledge is collected and generalized into laws or principles, the greater is its simplicity; in proportion as we increase in real knowledge, we increase in power; for the fewer these principles are, the more *general* does each of them become, and therefore the more extended in their application, and the more power must accrue from their knowledge. There is such an expansive property in all that is written down in the book of nature, that, like the revealed word of God, the more we study and ponder over its contents, the more does truth come up to light; something before unseen begins to appear; something that was dark gradually becomes light; that which was only light becomes gloriously effulgent. The Christian philosopher has therefore every encouragement to persevere in his inquiries, for if undertaken in a right spirit, they will lead to a more intimate communion with his Maker. As a Christian, he relies upon the goodness and mercy of God, through the merits of his Redeemer; and, as a philosopher, he relies upon the constancy of natural laws. When the inspired Psalmist calls upon all the works of Creation to praise the Lord, he gives the stability of nature as one of the reasons for the praise. He says, "Let them praise the name of the Lord: for He commanded, and they were created. He hath also established them for ever and ever: He hath made a decree which shall not pass." (Psalm cxlviii. 5, 6.)

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